April 1956
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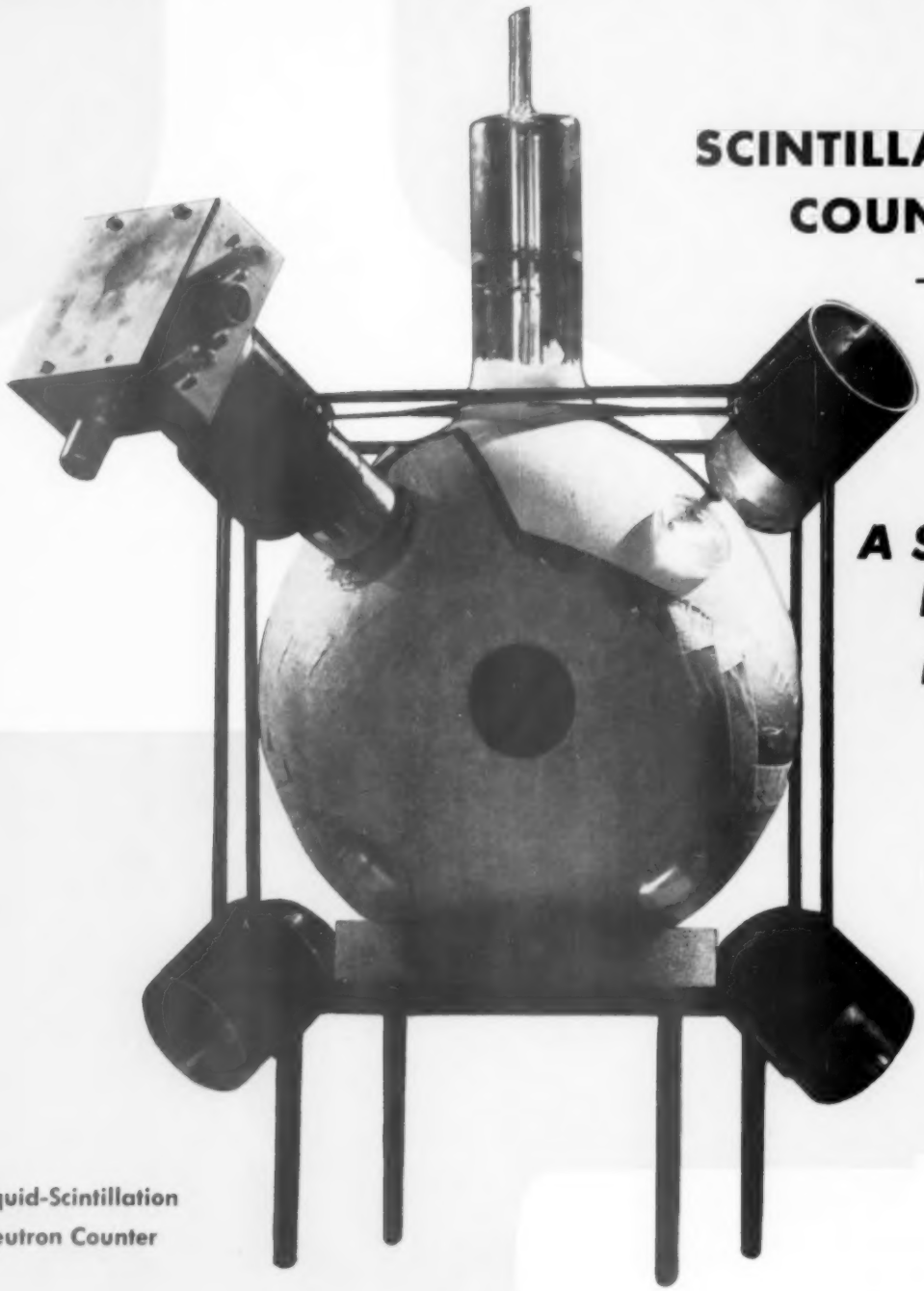
# NUCLEONICS

ATOMIC POWER • NUCLEAR ENGINEERING • APPLIED RADIATION

## SCINTILLATION COUNTING – 1956

**A Special Report**

page 33



Liquid-Scintillation Neutron Counter

ENGINEERING LEADERSHIP
KEY TO ATOMIC PROGRESS

# G-E Engineers "Cook" Fuel Plates at 1000° F. in Special Test Loop

Testing atomic products before they're built is a good trick—if you can do it.

One way General Electric engineers do just this is with a special test loop designed to simulate reactor core thermal conditions. Fuel element materials and designs can be pre-tested in this loop for void distribution and steam slip, steam blanketing, and heat transfer characteristics—all while the reactor is still on the drawing board.

Proving critical calculations like these *in the design stage* is another example of General Electric engineering leadership in the field of atomic energy.

Atomic Power Equipment Department, General Electric Company, Schenectady 5, New York. 1961

*Progress Is Our Most Important Product*

GENERAL ELECTRIC

# NUCLEONICS

**APRIL • 1956**

**Vol. 14, No. 4**



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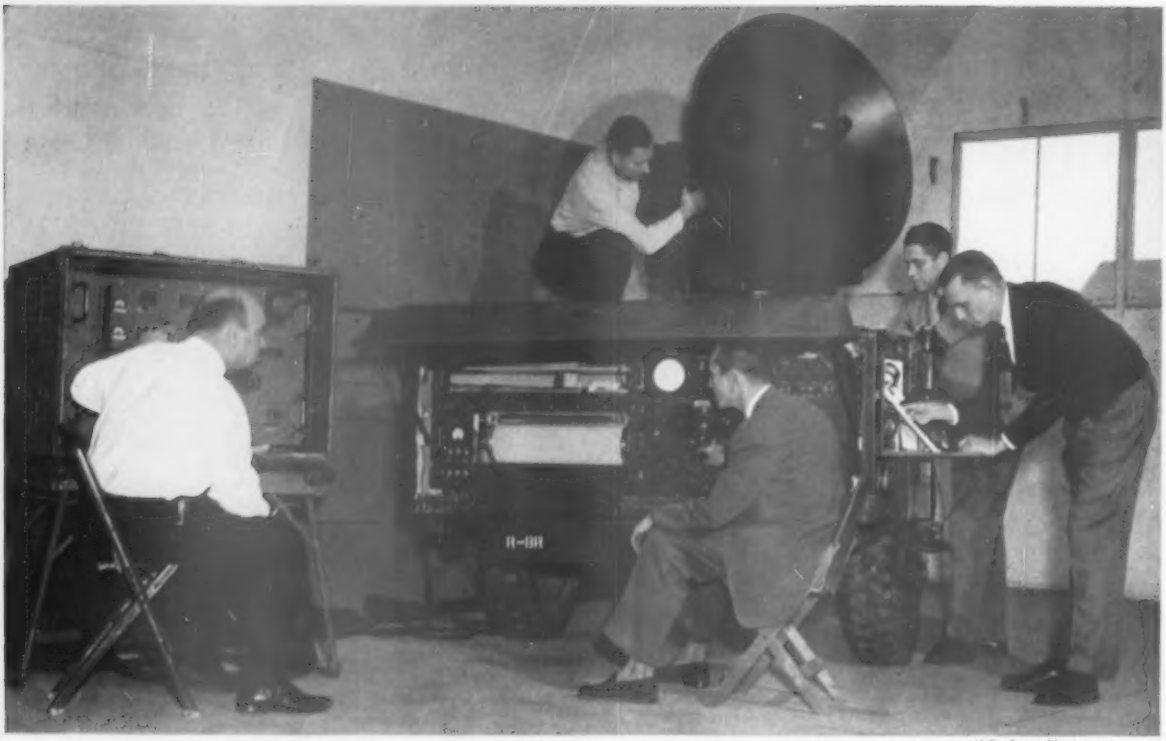

U.S. Army Photograph

Electronic specialists at Ft. Monmouth SCEL Laboratories checking out radar and computing system designed for field use.

# ARMY SIGNAL CORPS ENGINEERING LABORATORIES IS A CENTER FOR DEFENSE ELECTRONICS

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This is one of a series of ads on the technical activities of the Department of Defense. 102

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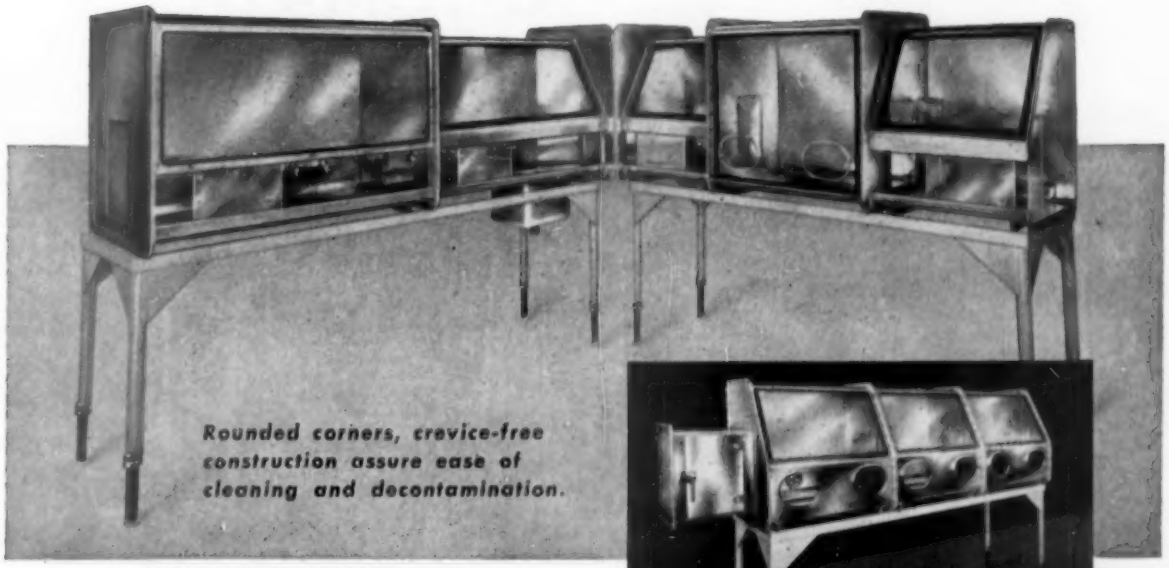
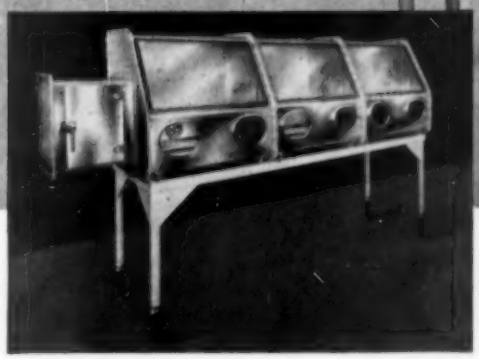
## FOR HANDLING RADIOACTIVE MATERIALS




Some of the many assemblies possible with the interchangeable dry box system.



***Here is a system of interchangeable dry boxes that offers several advantages:***

- Offers selection of six basic enclosures and variations, 2 types of air locks.
- Completely flexible. Endless arrangements are possible to meet any condition.
- Standardized adapter plates and gaskets provide for connecting any type box to another, with or without air locks interposed. Units can be re-arranged at any time.
- Standardized supports with adjustable legs accommodate any enclosure arrangement. Supports easily adapted to changes.
- All units promptly available for replacement, addition or re-arrangement.
- Variations in dimensions of any unit may be ordered to meet specific conditions.

**SEND FOR TECHNICAL BULLETIN A-4** providing additional information about this interchangeable dry box system.

**OTHER TECHNICAL BULLETINS AVAILABLE**

• This is only a partial list. Ask us about the specific equipment in which you are interested.

**A-1** Stainless Steel Low Intensity Dry Box
**A-2** Stainless Steel Vacuum Dry Box
**A-5** Biological Safety Cabinets & Research Enclosures
**B-2** Dry Radioactive Waste Container
**D-3** Typical Radio-Chemical Laboratory
**E-4** Los Alamos Type Vacuum Rack Enclosures
**E-5** Los Alamos Type Stainless Steel Fume Hood
**E-6** Hanford Downdraft Fume Hood

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Write for the general instrument catalog, or request information to help you solve your specific problems.

**Nucleonics, Vol. 13, No. 11—Nov. 1955—P. 82.*

*Write for instrument catalog showing models and prices*

**WELL COUNTER**

Unusually complete shielding, with two full inches of lead around the full length of the counter, provides maximum gamma sensitivity with lowest background. Specifically designed for measurement of small volume samples containing gamma emitting isotopes of the order of $10^{-10}$ curies.

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*A Division of Nuclear Corporation of America, Inc.*

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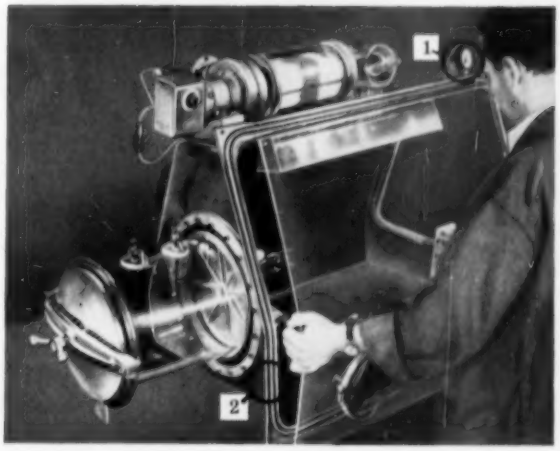
**"LEAD-RUBBER" GLOVES** that permit handling of low levels of beta radioactive materials. The gloves are soft and as pliable as heavy leather. They are made in a choice of thicknesses equaling 1 to 5 mm. lead shielding. They are designed to fit standard "O" ring systems employed in "Dry-Glove" boxes.

# NEW TOOLS

## for the Nuclear Industry

**No. 13 "SAFETY-GLOVE" BOX.** Transparent plastic housing with ¼" thick chemical and scratch resistant observation-glove panel. Shown is the simplicity in removing the 36" x 24" front observation-glove panel from the Safety-Glove box. Note the air gauge (1) and the inflatable plastic gasket-tube (2) which encircles the "Box." The patented inflatable gasket system allows the opening and closing of the entire "Dry-Box" to and from a hermetic state within seconds.



**TWO SIZES: 36" x 24" x 18", 48" x 30" x 20".**

**"SAFETY-GLOVE" BOXES** are now cast into a one piece "bottle like" housing of unbreakable and high heat resistant Polyethylene. The housing can be steam sterilized and has excellent chemical resistance. It is absolutely impervious to all acids. It is light and portable. Stainless steel housings are also available — with the same Lennard patented features and controls.

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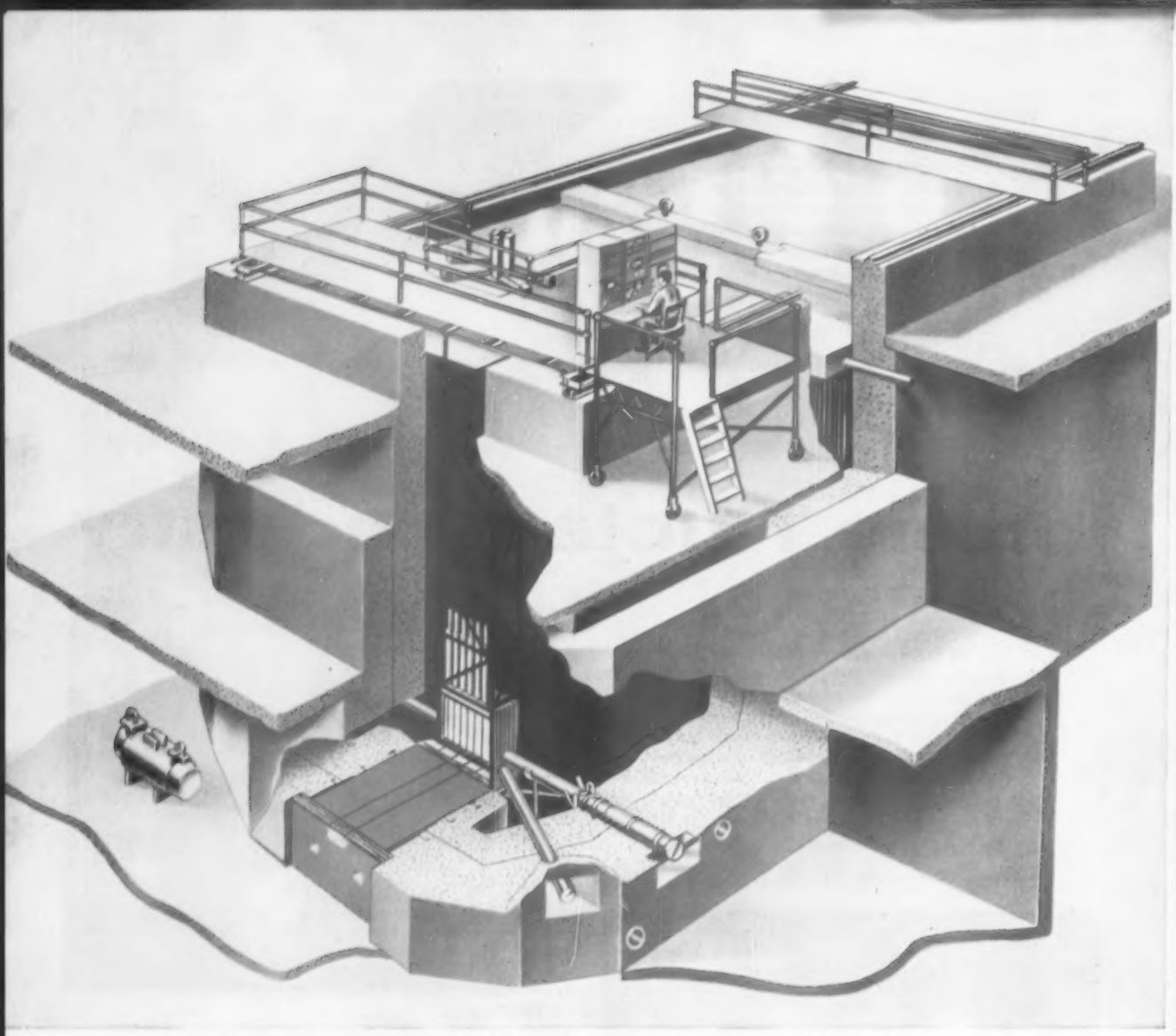
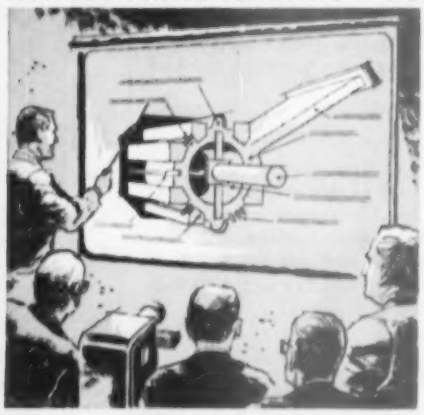


**SWIMMING POOL REACTOR,** one of three G-E research reactors available under the 7-point program, is designed to produce large quantities of neutrons. Its flexibility, safety features, and high flux potential appeal to universities and research organizations.

## NEW GENERAL ELECTRIC 7-POINT PROGRAM:



**1 REACTOR SPECIFICATIONS** are prepared to meet your research requirements. These include a report on core, control, and reactor components.

**2 BUILDING STUDY** also includes complete co-ordination of all plans for the many facilities required in the reactor and laboratory buildings.

**3 HAZARDS SUMMARY REPORT:** We help you prepare study for submission to AEC Division of Civilian Application.

# How General Electric can help you enter advanced nuclear research fields

## New G-E 7-point program simplifies procedure for obtaining a nuclear research reactor

There is more work involved in obtaining a nuclear reactor for advanced research than simply ordering one. Specific research requirements must be determined beforehand, an appropriate design selected, and necessary AEC construction permits and licenses obtained. Other essential steps are covered in the program outlined below.

**NEW GENERAL ELECTRIC 7-POINT PROGRAM** is a plan designed to materially aid you in putting a research reactor to work. Through this program you can obtain any one of three General Electric research reactors: The Swimming Pool Reactor, Heavy Water Research Reactor, or the Nuclear Test Reactor.

**FOR MORE INFORMATION** on these three research reactors and the new General Electric 7-point program, write for bulletin GEA-6326, General Electric Company, Section 191-1, Schenectady 5, N. Y.; or contact your nearest G-E Apparatus Sales Office. Outside the U. S. and Canada, write to: International General Electric Co., Inc., 570 Lexington Ave., New York, N. Y.

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**4** **MANUFACTURE OF REACTOR** is accurately co-ordinated with other construction plans, thereby assuring centralized project scheduling.

**5** **REACTOR INSTALLATION** is completed at the site by the men who have followed the design and manufacture of the complete system.

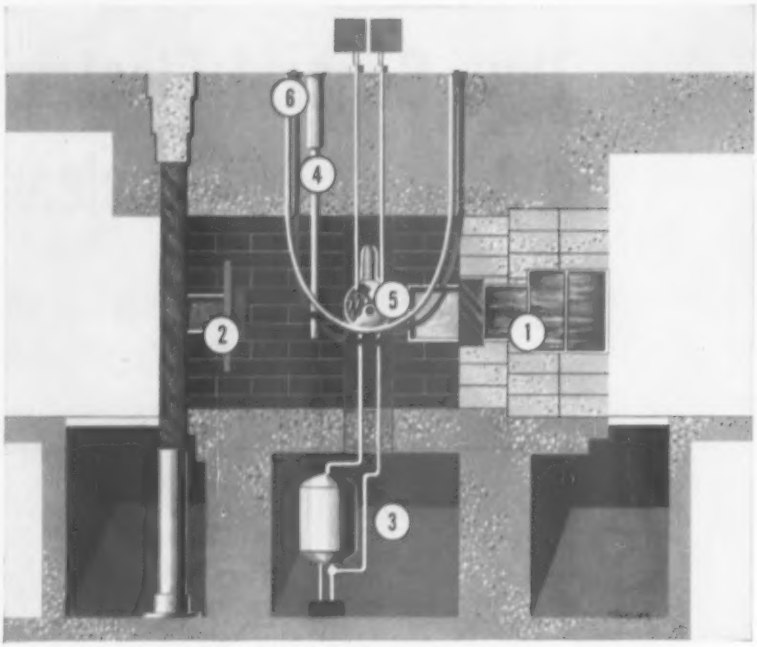
**6-7** **START-UP AND SERVICE** by experienced personnel is added assurance that proper operation of your nuclear system will be maintained.

# NUCLEAR NEWS FROM ATOMICS INTERNATIONAL

## Nuclear Reactor for Cancer and Other Medical Research

This new reactor utilizes the proven homogeneous solution design based on the SUPO unit at Los Alamos—modified and adapted to the special needs of cancer and other medical research and therapy. To be built by ATOMICS INTERNATIONAL for a prominent southern California university Medical Center, the reactor will provide a variety of radiological facilities—primarily high purity neutron and gamma beams with controlled exposure times in each. The thermal neutron flux at the central exposure tube is $1.7 \times 10^{12}$ n/cm²-sec. at a power of 50 Kw.

Gas handling system assembly for nuclear research reactor. This component, developed by Atomics International, contains facilities for circulating the reactor atmosphere, recombining the radiolytic gases, condensing the water vapor and returning water to the reactor core, in a closed cycle operation. Additionally, the tank at top which contains fission product gases, provides an intense source of neutron-free gamma radiation.




Medical Reactor Test Facilities

1. Gamma and Fast Neutron Facility—Gamma intensities of 1.3 reb/min/Kw and fast neutron intensities of 4 reb/min/Kw are available.
2. Thermal Neutron Facility—Provides neutron flux of $3.8 \times 10^7$ n/cm²-sec. per kilowatt.
3. Gamma Radiation Area—Activity of the fission gases provides a radiation source in the gas handling equipment room.
4. Multiple Specimen Irradiation Tube—One or more in the reflector. Each accommodates 16 samples.
5. Central Exposure Tube—A 1-inch internal diameter tube through the center of the core permits access to maximum neutron flux.
6. Pneumatic Tubes—Tangential to core. Also (not shown) are Beam Tubes—Radial to core, or through reflector tangential to the core.

**One Configuration** of the thermal neutron facility provides a neutron flux of $3.8 \times 10^7$ n/cm²-sec/Kw with a gamma ray intensity of only 0.1 reb/min./Kw (reb—roentgen equivalent biological). The fuel is Uranium enriched in the $U^{235}$ isotope in the form of $UO_2SO_4$ dissolved in light water. This fuel-moderator solution, cooled by chilled recirculated water, is contained in a stainless steel core tank surrounded by a graphite reflector and dense concrete shield. Radiolytic and fission gases produced in operation are handled in a closed-cycle, water recombination and return system, which eliminates any discharge of radioactive core effluents and permits the re-utilization of materials.

**Atomics International** is a major reactor builder—experienced in the design, construction and operation of nuclear reactors for research and the production of power. If you are interested in any phase of our activities, ATOMICS INTERNATIONAL is staffed and equipped to help you. Please write: Applications Engineering Service, Dept. N-N1, ATOMICS INTERNATIONAL, P.O. Box 309, Canoga Park, California. Cable address: ATOMICS.

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PIONEERS IN THE CREATIVE USE OF THE ATOM

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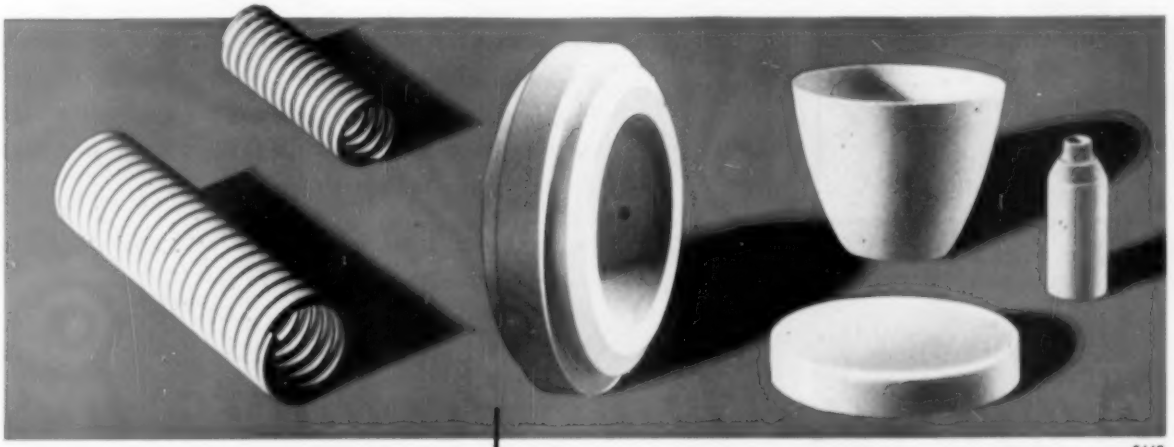
How is it used? In such mechanical applications as rotating seals, pump plungers, slide valves, cutting tools, sleeve bearings, bushings, extrusion dies. In electronic applications as tube envelopes, as insulating supports. It can be joined to itself or to unrelated materials with a vacuum type bond.

Certainly, any engineer concerned with material specification in mechanical, electronic, or nucleonic design problems should be thoroughly familiar with Alite and its possibilities. Bulletin A-7 tells the story. It is free on request. Write for it today.



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**INPUT**
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at approx. 5 m.a.

**OUTPUT FREQUENCY**
400 or 500 cycles

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+ —.02% from —65° to + 85°C.

Type R2007T
+ —.002% from + 15° to + 85°C.

Type W2007T
+ —.005% from —65° to + 85°C.

**OUTPUT VOLTAGE**
5 volts, sine wave.

Substantially uniform
from —65° to + 85°C.

**LIFE EXPECTANCY**
several times that of vacuum tubes

**INTERNALLY SHOCK MOUNTED**
on Silastic

**MAGNETICALLY SHIELDED**

**HERMETICALLY SEALED**

**OCTAL BASE**

**SIZE**
4½" x 1⅝" diameter

**WEIGHT**
7 ounces

**COMPLETE INFORMATION ON REQUEST**
**PLEASE SPECIFY TYPE 2007T**

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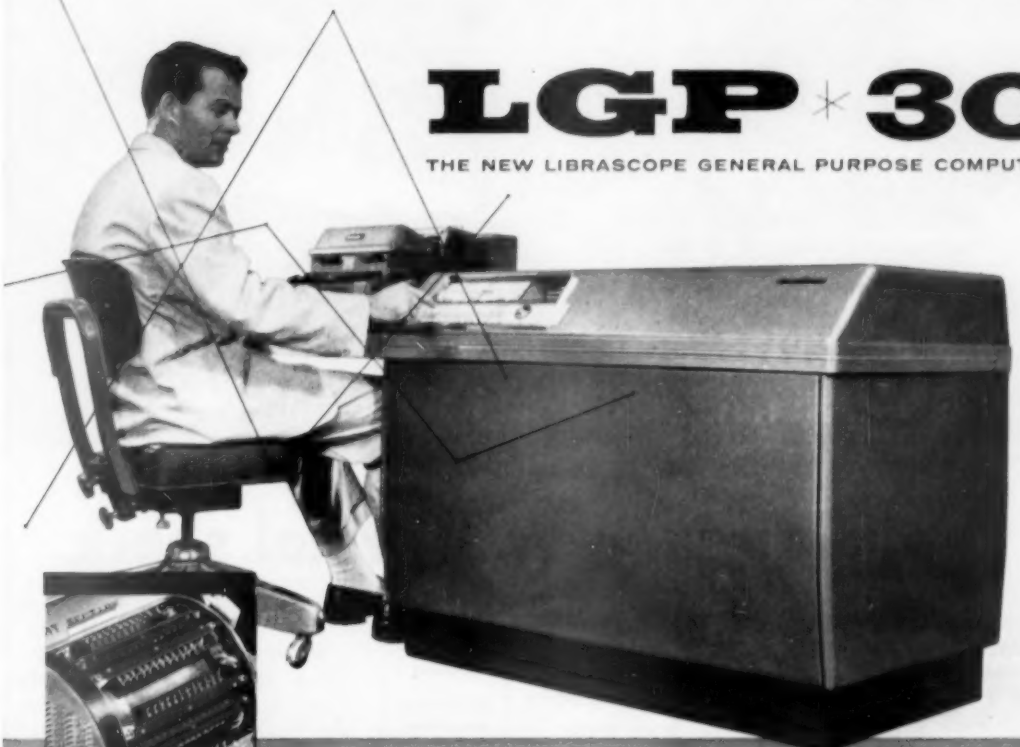
# the new approach to large scale computations in nuclear research–development!



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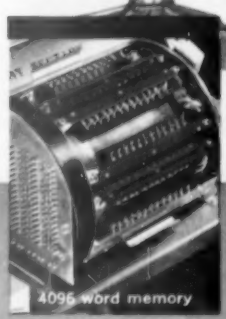
THE NEW LIBRASCOPE GENERAL PURPOSE COMPUTER



4096 word memory

**SPECIFICATIONS:**

Word length:
30 bits, and sign
Mode of Operation:
Serial, one address
Program Storage:
Internal
Access time:
8.5 ms av. 2 ms min.
Transfer time:
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+ time: 26 ms
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Power: 1500 Watts

One word defines the "new approach" of the LGP-30...SIMPLICITY. *Operating Simplicity*...for the average engineer...made possible by the elimination of non-essential commands. Programming techniques are easily mastered. *Design simplicity*...that results in complete mobility. The LGP-30 may be operated from any 115 Volt AC outlet. *Service simplicity*...because fewer components, conservatively operated, mean less "time-out" for maintenance. And, too, the LGP-30 costs considerably less than any other general purpose computer—to buy and operate.

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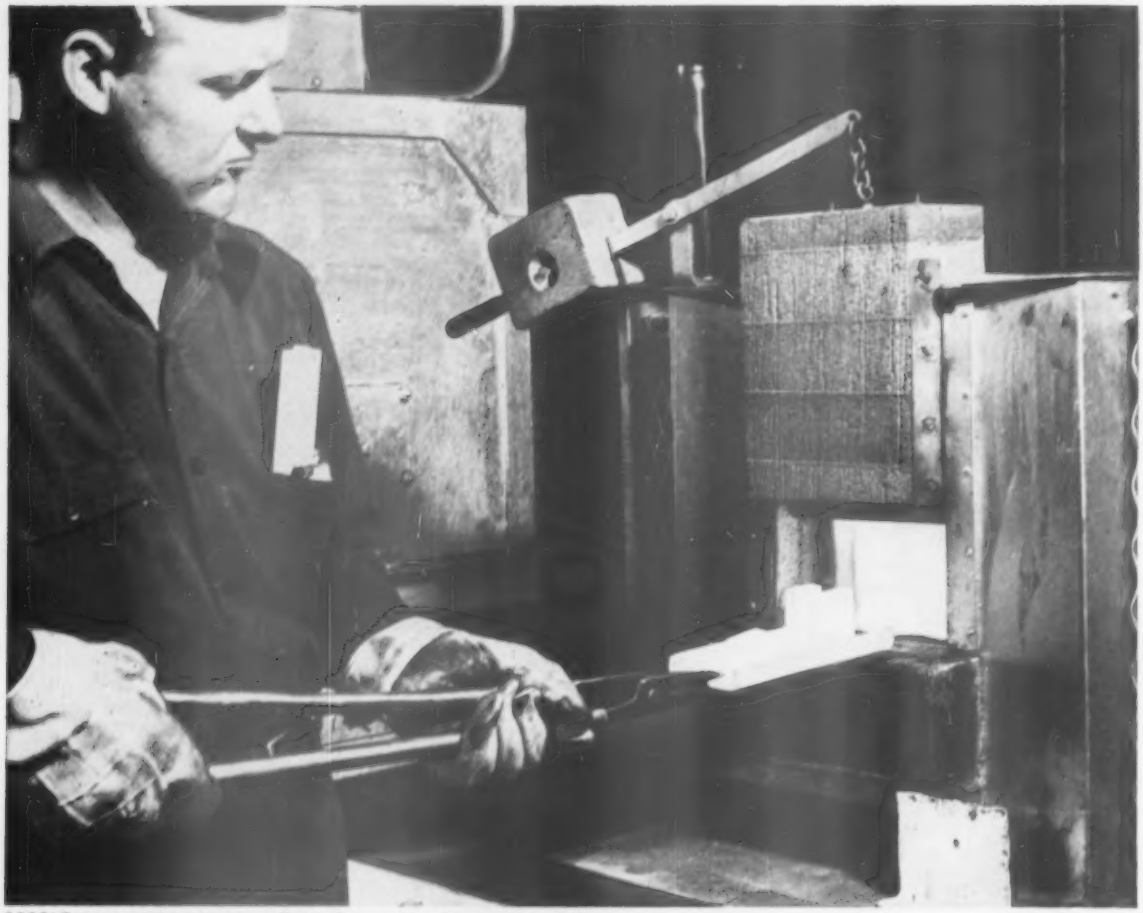

**2300° F. to room temperature.** Inconel trays take this shock in stride.

# This INCO alloy ignores thermal shock

Under some conditions, only Inconel* nickel-chromium alloy combines all the needed forms of heat- and corrosion-resistance.

Take trays for the tiny furnace shown above. They plunge from 2300°F. to room temperature and back again. Too much for ceramic trays! Within five months, thermal shock shattered ninety. Yet it was thought that only a ceramic could provide resistance to deformation and scaling.

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In heat-treating, in high-temperature chemical processing, in jet aircraft engines . . . Inconel has long met the need for a metal that ignores severe high-temperature conditions.

**Inconel** . . . *for long life at high temperatures*

**Get engineering data from Inco**

For help in solving immediate high-temperature problems, contact Inco's Technical Service Section . . . giving full details if possible.

For your files, send for Inco's 24-page Technical Bulletin T-7. It discusses Inconel properties, describes fabrication, lists available forms. Write:

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**Inconel alloy is mechanically stable.** It retains useful properties to 2100°F. and over, in some applications. It resists grain growth and withstands thermal shock.

**Inconel alloy is easy-to-work . . .** easy to form, machine, weld . . . available in all commercial wrought forms.

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*Nuclear problems...*

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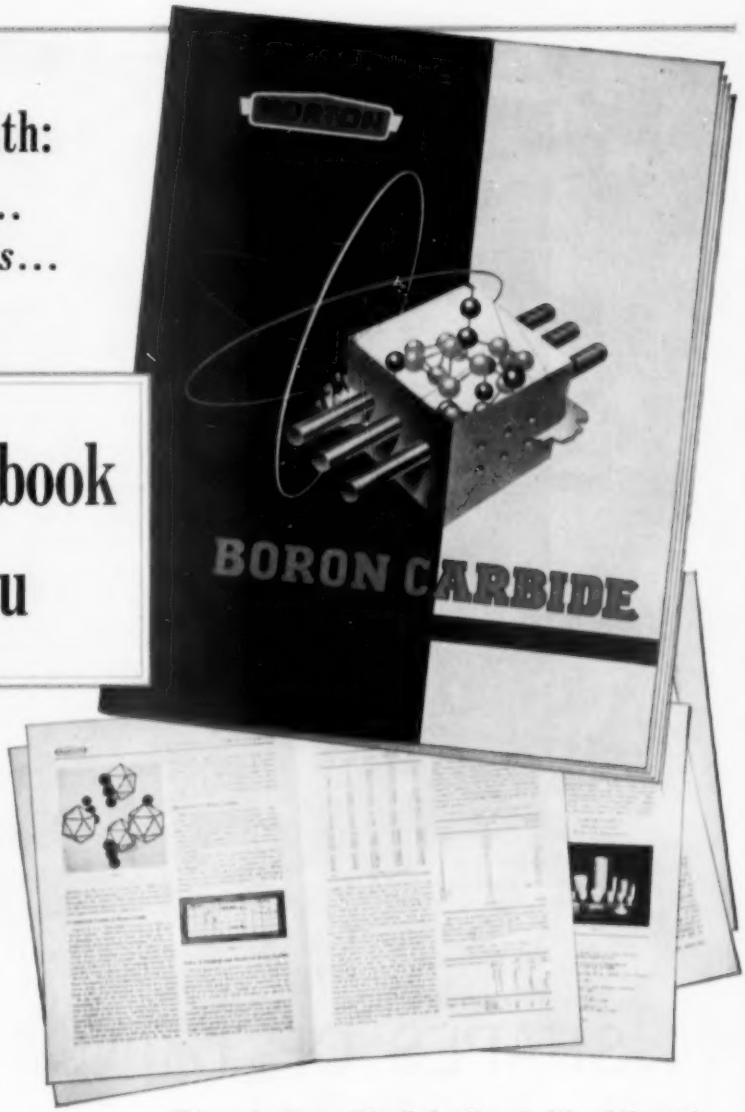


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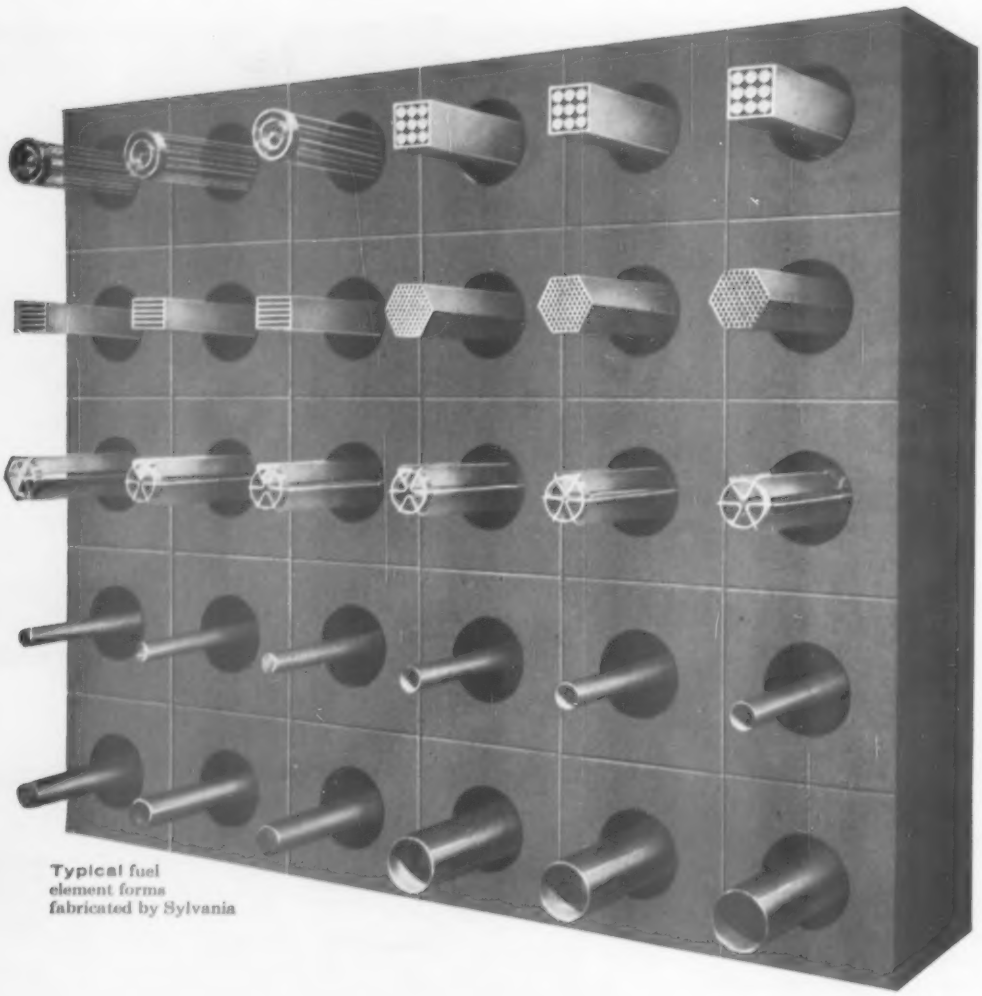

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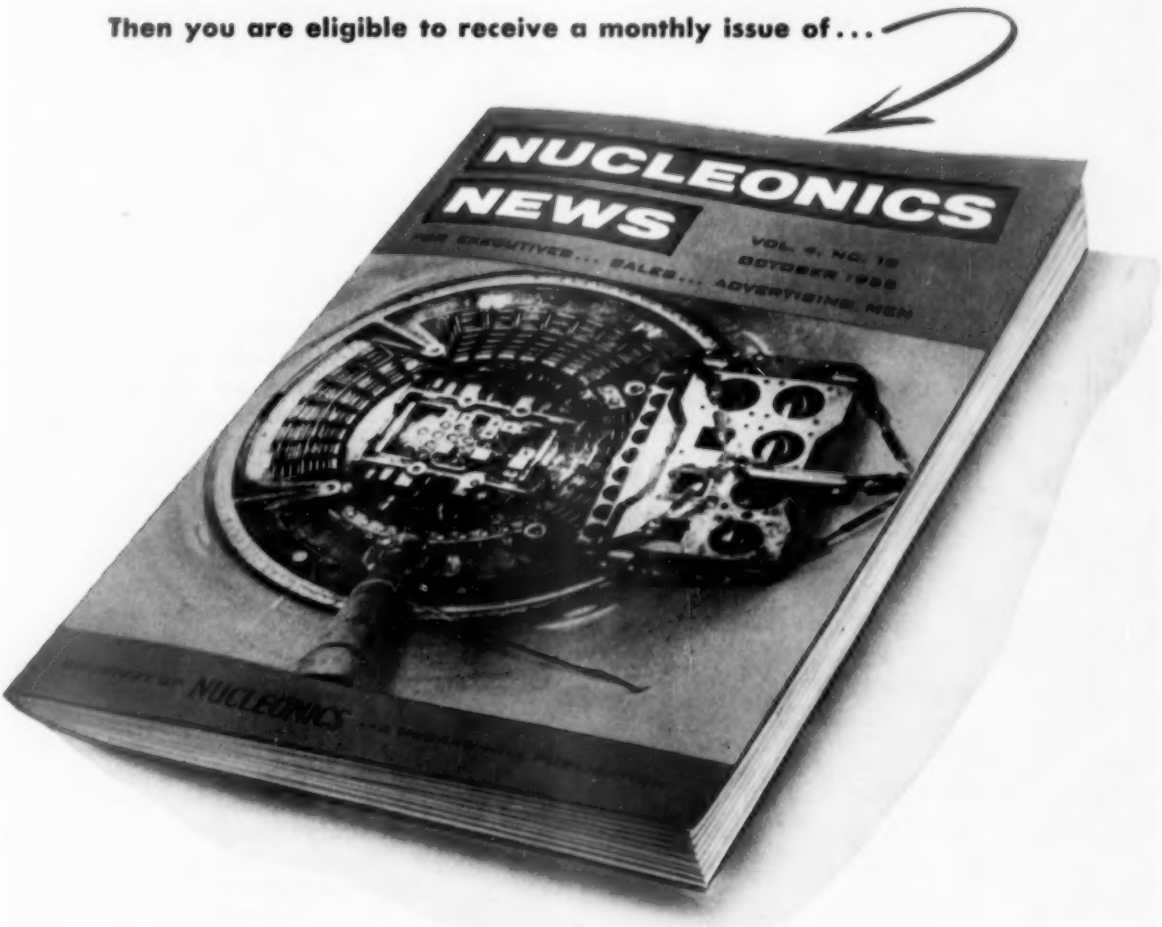


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# ROUNDUP of Key Developments in Atomic Energy

## LATE NEWS and Commentary

**4 Sales Abroad**

It's been a busy month for U. S. reactor exporters: the first four research reactors were sold for delivery abroad by private firms (up to now, the only research reactor for overseas was sold by AEC, to Switzerland; the only private reactor sale was the Belgian World's Fair power reactor by Westinghouse). Italy contracted with American Car & Foundry for a CP-5 (ACF is building another for MIT). Atomics International sold to Japan a $250,000, 50-kw water boiler similar to the one it built for Armour Research Foundation; it is to be delivered to a site near Tokyo within one year. Babcock & Wilcox sold a 5-Mw swimming pool to Brazil for delivery in a year, probably at São Paolo. And General Electric sold a 3-Mw swimming pool to Spain for erection in the Moncloa area near Madrid. The purchaser in each case is the foreign government.

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**Four Bid on First A-Ship**

Four companies—Babcock & Wilcox, Foster Wheeler, General Electric and Ingalls Shipbuilding Corp.—have given the Maritime Administration bids to build a modified Nautilus-type PWR for a $22.5-million tanker to be in operation by June 1959. Nine companies offered to build, or to conduct research on, a more advanced power plant—probably a closed-cycle nuclear gas turbine using helium as system fluid—for a second atomic tanker to go into service in 1961. Only GE bid on both jobs. The other eight companies interested in the long-range project are American Turbine Corp., AMF Atomics, Ford Instrument Co., General Dynamics (General Atomic division), General Motors (Cleveland Diesel engine division), North American Aviation (Atomics International division), Nuclear Development Corp. of America, and Stanford Research Institute. Conspicuous by their absence from these lists are Westinghouse and Newport News Shipbuilding and Dry Dock Co., the two firms hitherto most prominently identified with atomic merchant ship projects; the word is, however, that while both chose not to figure as would-be prime contractors, both are associated with bidders—Westinghouse with Ingalls, Newport News Ship with B&W and DeLaval Steam Turbine Co.

Both projected ships would be in the supertanker class: about 38,000 tons displacement, 22,000 shaft horsepower, 20–21 knots. The PWR-powered tanker, which could be used initially as an atoms-for-peace demonstration ship and then converted to commercial hauling operations, could easily be built for the $22.5-million asked in the current budget; the gas-cycle ship would cost more to develop and build. Last year Congress adjourned before completing action on authorizing an atomic merchantman, but chances are said to be better this year although an intercommittee jurisdictional squabble has yet to be resolved. Maritime disagrees sharply with nuclear navy chief Admiral Rickover, who recommended to the McKinney Panel against starting to build an atomic merchant ship until after one that "promises economic advantages over conventional" types has been both designed and experimentally verified. Maritime feels even a PWR-type engine (which Rickover says has "small possibility of becoming economically feasible for commercial ships") looks so good that at worst it would be only 40% above a conventional ship in cost, at best would compete, and in either case would show a profit with only the size of the profit margin in doubt. Although Britain, France, Norway, Germany and Japan have all talked atomic merchant ship, no one has yet gone beyond paper studies, and it is widely conceded that for all practical purposes the U. S. can be as far ahead as it chooses.

**Enter Yttrium**

AEC has asked 54 companies for bids on supplying yttrium. The exotic metal has a neutron absorption cross section higher than zirconium but lower than stainless steel; no one knows much about its behavior, and AEC wants to test its potential uses, presumably in fuel elements. It seeks 500–1,500 lbs $Y_2O_3$ monthly.

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**Upturn for World Agency**

In one of its sudden unexplained policy shifts, the Soviet last month dropped its long-standing insistence that the proposed World Atomic Agency be subject to the U.N. Security Council—that is, the Russian veto. As a result, prospects for creation of an effective agency look brighter than at any time in the 28 months since it was first proposed. A 12-nation conference in Washington hammered out a new draft charter for the Agency (an earlier draft last fall elicited too many reservations). After consulting their governments, the conferees will meet again in Washington April 9 to sign the draft charter, which then will go before an 84-nation meeting in the fall for final approval. A second major shift that made agreement possible was a rapprochment, at least in part, between India and the U. S. on safeguards. India has taken a strong stand against the tough inspection and control policy demanded by the U. S. to insure against diversion to military uses, which India feels would have the deleterious effect of dividing nations into two categories: those receiving aid from the agency and those not. New Delhi holds that a certain measure of confidence is indispensable; that many independent countries could not agree that all new fissionable material produced by them should be deposited in a World Agency bank unless this is agreed to on a universal basis and not imposed only on countries receiving aid from the agency; that otherwise this would be as absurd as requiring some families to keep their dinnerknives in a communal cupboard between meals because knives can also be used to cut people's throats. A new formula on the relations between the U.N. and the proposed Agency, acceptable to both countries, may be contained in the new draft.

Meanwhile the United Nations Scientific Committee on Radiation concluded its first session with adoption of an ambitious program for charting the levels and effects of every kind of radiation on all the world's population (*details p. 24*).

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**Secrecy Hit Again**

James G. Beckerley, former director of classification for AEC, added to the protest against keeping the secrecy label on controlled fusion work (see also pp. 21B, 24). He told the Joint Congressional Committee on Atomic Energy that the McKinney panel had been wrong in failing to recommend "release of information on a device which no one knows how to make, and which may never even be possible to make . . . The monopoly of an entirely new area of basic study by an agency of the Government and the effective denial to scientists and engineers of the right to work (or even to think) in this field is not a proper function of the Government except possibly during the extreme situation of war.

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**Test Pile Plan Dead**

The plan for a super-high-flux ($10^{15}$n/cm²/sec) industrial test reactor to be built in New England by a combine of firms taking pile time (NU, March '56, p. 22) is a "dead duck." It can now be revealed that Textron Corp, hitherto not identified with atomic energy, was prime mover of the project through a subsidiary, Nuclear Reactors Inc. Textron dropped the project last month when it failed to get enough "interested" companies to put up cash for the $12–20-million facility. General Electric was to have built a three-headed reactor system: three cores arranged in a triangle, with 360-deg access to each one for testing, and a cooling capacity permitting any two cores to operate while the third was being refueled. A. D. Little, who were consultants and would have been operators of the facility, have not given up, hope to start anew.

## Survey Shows Great Interest in U. S. U-235

For some time, particularly since the Geneva conference, much of the free world has been waiting expectantly to learn whether it could count on the U. S. making available enriched uranium for power reactors. A month ago the question was answered when 20,000 kg of $U^{235}$ was earmarked for reactor programs abroad. To get a reliable report on reaction abroad, NUCLEONICS polled 15 capitals; answers were obtained from top responsible officials in the countries' atomic energy agencies.

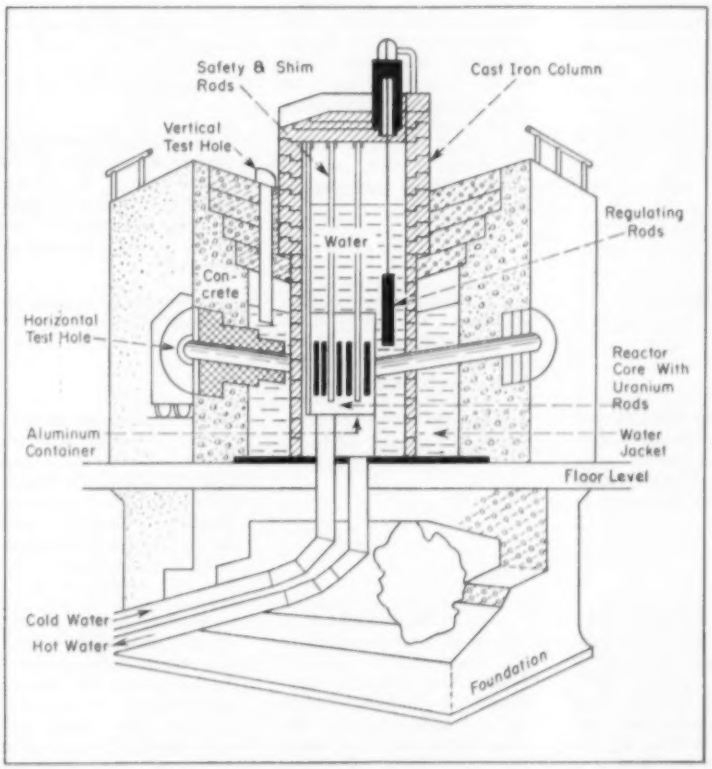
**The NUCLEONICS survey begins on the next page.**

Some countries found the questions premature. Mexico, for instance, has not yet appointed her AEC; this is expected by month's end. Australia knows she is interested in procuring enriched U, is in touch with Washington on the matter, but has as yet made no decisions regarding amounts and enrichments needed, reprocessing policy, etc. The Netherlands declined comment (only one to do so) on the ground this is a matter of "internal policy."

At the other extreme from countries just beginning is Britain, only Western-bloc country specifically excluded from the offer (she is herself a producer of enriched U). Britain gets her natural U partly through arrangements in Australia and Rhodesia, but mostly through the Combined [US-UK-Canada] Development Agency from South Africa and Belgian Congo. Although her gaseous diffusion plant is much smaller than the Oak Ridge complex—hardly large enough to meet her own needs—Britain is nevertheless making enriched U available to four other countries: France, Belgium, Denmark and India. The British welcomed the U. S. offer as an "important contribution" to peaceful atomic development, found the quantities "surprisingly large."

The NUCLEONICS survey showed near-unanimous demand for enriched U. On the controversial point of enforced U. S. reprocessing, however, there was a split with more than half the replies indicating either no interest in reprocessing or no capability to do so for some time. Another striking thing was the spread in knowledgeability about atomic power, with some nations showing considerable sophistication, others equal naiveté.

Reactions of 11 key countries are on the next three pages.




CZECHOSLOVAKIA'S first reactor, furnished by the Soviet Union, was shown in the Prague daily *Rude Pravo* a month ago. This research reactor is evidently the model that Russia is giving all her satellites. A swimming-pool type (or perhaps better described as a well type), it is of simple design, uses 10% enriched U fuel arranged in 823 rods 7.5 mm apart and contained in aluminum tubes of 10 mm diameter, 50 cm long. The reactor itself is 7½ × 8½ × 12 m high, develops 2,000 kw heat. Test holes up to 4 m long have remote-control equipment for inserting samples

## Libby Woos Chem. Industry

"Why is it that the chemical industries are relatively unknown in atomic power?" AEC Commissioner W. F. Libby, himself a chemist, asked last month at—of all places—a power industry conference. "It probably has to do with a feeling that atomic power is not a chemical business. I would suggest that it *is* after all a chemical business," Libby pursued in a frontal attack on the prevailing view in chemical industry management that it's utility territory. "If the skills possessed by the technical staffs of some of our larger and most efficient chemical companies could be made available, we would certainly attain economically competitive atomic power sooner."

(DuPont and Union Carbide & Carbon operate vast AEC facilities; Dow is doing LMFR research. Monsanto and American Cyanamid, formerly active, have withdrawn from the field.)

Libby held out two lures: (1) "It is by no means clear that fission products cannot be made useful and profitable if the talents of more chemical technologists were applied to this goal; it may be that atomic piles will be needed by chemical plants simply to supply enough radiation for just this one use. Why, then, could not atomic power also be made?" (2) "Tremendous quantities of waste heat are available from every reactor. It is not at all unlikely that such large quantities of heat will be of use in chemical processing."

# Reaction Abroad to U. S. Offer of Enriched Uranium:

| QUESTIONS | FRANCE | BELGIUM | W. GERMANY |
|---|---|---|---|
| **1.** Is country interested in importing enriched U? | Yes. | We are already getting all the enriched uranium we need for both power and research under our power bilateral with the U. S. | Highly interested.* |
| **2.** Is country interested in importing enriched U from USA? | Yes. The possibility of getting $U^{235}$ in the next five years, during which we couldn't produce it, is extremely important. | | Equally highly interested ("Where else should we get it?") |
| **3.** What's the anticipated need next year? in next 5 years? next 10 years? | Our plans are completely upset by this offer; new ones have not yet been developed. Heretofore we planned on the basis of 100 kg of Pu annual output at Marcoule. The availability of $U^{235}$ now will permit us to develop power experience much earlier than anticipated. The second commercial power plant, scheduled to operate in 1961, will now use American $U^{235}$. | It depends on the results of the USAEC five-year program. If the results are good, and we can attain economically competitive power, then we'll have a large need; if not, it will be a different matter. | Very hard to estimate now. Based on one or two power plants (aside from 2 or 3 research reactors covered under research bilateral's 6 kg), perhaps 25 kg additional in first year. Predictions for 5–10 years "utterly impossible" as no German reactor program has been agreed on yet. |
| **4.** Is country more interested in buying or leasing enriched U? | No decision yet, pending establishment of U. S. conditions governing sale and lease. | Buying. But it depends on the terms and conditions. | Depends on terms offered. |
| **5.** Does country want to do its own reprocessing? | We would "probably" like to do own reprocessing, to have a complete cycle of operations, but . . . | Under our power bilateral, we must send back spent fuel for reprocessing. The amounts that need to be reprocessed are now very small; but there may be joint European reprocessing if the security problems can be solved, perhaps under the Euratom plan, and we would be very interested in that. | Yes—definitely. |
| **6.** Would country accept American reprocessing as a condition of obtaining enriched uranium? | . . . we would probably agree. | | Would agree so as to obtain U at all. But it's expected here U. S. will later sell U to Germany for power reactors; once we own some U we would reprocess domestically. |
| **7.** What degree of enrichment of U is desired? | Not yet known. | For most purposes 1–2% is sufficient. For the MTR we are now planning, a higher enrichment than the 20% limit may be necessary. | Normally up to 20%; in a few exceptional cases, 50–60% would be desirable. |
| **8.** What has or will be done to get U. S. uranium? | The Foreign Minister and the U. S. Ambassador discussed this in Paris in early March, and French AEC representatives are now in Washington. | Does not apply to Belgium. | Under research bilateral, Germany will get 6 kg; this is the only step taken up to now. Further initiative will "probably" be taken by Atomics Minister Franz Strauss on his planned trip to U. S. this spring. |
| **9.** What other reactions to the U. S. offer are there? | The offer should be basically a stimulus to French, and other, national efforts in the nuclear power field, should not be thought of as a replacement for such efforts. For example, importing 2 tons of enriched U a year for 5 years would produce by the end of 10 years only 1% of French power requirements. | We are like the laborer in the parable who worked in the vineyard from the first hour. Now laborers coming at the eleventh hour are to get the same as we. We must work fast and make the most of the advantage our power bilateral gives us, because in 1–2 years all countries may have the same thing too. | We feel sure we will get an adequate share of U. S. U-reserves, and that the bilateral is only the first step in German-U. S. cooperation in this field. Major question unsettled concerns the terms of the offer; also whether high costs would make a European isotope separation plant sensible. |

* Research bilateral contains a clause much regretted here: that leased U be delivered in sealed status and be returned still in sealed status. If the same condition is imposed in future, Germany would by far prefer to buy her own uranium to circumvent the "embarrassing condition" that German institutes and scientists be prevented from watching the changes taking place in the uranium.

# A Nucleonics Survey . . .

| ITALY | NORWAY | SWEDEN | SPAIN |
|---|---|---|---|
| Keenly interested. | Yes. | Yes . . . † | Yes. |
| Very willing; however, if enriched U were offered by other countries, we would apply to the one offering the best conditions. | Yes. | Yes. Already getting 6 kg under research bilateral. "Probably the only place we can get it." | Yes, but with some reserve pending more specific details of offer. |
| 1957: adequately covered under the research bilateral. Difficult to estimate needs in next 5–10 years, as the future nuclear program has not yet been drawn up. | 1957: 15 kg.<br>1961: 100 kg. | Impossible to give brief answer, due to technical considerations. All power and heating plants planned to date designed for natural U; in any case we will use enriched side-by-side with natural U, possibly using enriched to spike natural U instead of going to fully enriched designs. | 1957: none. 1961: maybe 60,000 installed kw nuclear. 1966: 1-million installed kw nuclear. |
| Will be leased—implying return for reprocessing, and maintenance by U. S. of a steady supply. | Leasing. | If leasing means sending it back after a certain number of kwh have been removed, we would prefer to buy, to build up a stockpile of Pu for reactor use. | Buying. |
| We will for a long time not find it expedient to erect a reprocessing plant, as its cost would not be proportionate to the small quantities of U to be reprocessed. | No, but we want to be free to do some experimental work on reprocessing. | We want and plan to do own reprocessing, but are not ready yet. A great deal of preparatory work has already been done; in 4–5 years we will have our own reprocessing pilot plant. | Yes—or with a regional agreement among neighboring countries. |
| We have already accepted this principle in research bilateral. | No. | In principle, we would probably accept this condition at first, but later on might want to do our own. At first might even prefer to lease U until we built up our own reprocessing facilities. | Undecided. Such terms would be regarded as tough. |
| Heavy enrichment desirable. | 1–2%. | A slight enrichment may be sufficient for Swedish power plants. | As high as possible, to 90%. |
| In January the head of the Italian Nuclear Research Committee, who had negotiated the research bilateral, went to Washington to implement it and to negotiate a power bilateral. Negotiations for enriched U for power reactors are going on. | In Nov. 1955 asked for 30 kg of 2% and a commitment for 10 years. | No official move has been made, but informal contacts have been opened to learn more about the offer and its conditions. | Nothing so far. |
| It may greatly hasten research work and plans for industrial atomic power. | None. | Interesting, useful and generous offer. Raises the question whether more than 6 kg might be available for research within the present standard agreement. | An important step forward in the development of advanced power reactors, but somewhat unspecific as to quantity and enrichment. "We cannot make adjustment before we know the amount per year and per country the U. S. is willing to give; therefore we are waiting for more precise and detailed statement." |

† . . . if we can obtain continuous supply, guaranteed independent of changing political conditions. Also we want to consider economic advantages of natural U, which is domestically unlimited, as compared to enriched. Finally, question is raised whether offer will in any way be tied to purchase of U. S. reactor equipment.

## Survey on Reaction to Uranium Offer (Cont'd.)

| | INDIA | JAPAN | ARGENTINA | BRAZIL |
|---|---|---|---|---|
| 1. | Yes . . . § | Yes, very interested. | Yes. | Unequivocally yes. |
| 2. | Yes, wherever we can get it on favorable terms. We are already getting some from Britain for our swimming-pool reactor; we'd be glad to get some from the U. S. | Yes, we hope to import most of our U needs from U. S.; what we can't get, from Britain. | Yes. If Argentina buys a 100-kw research reactor, importation of enriched U will be a precondition of purchase. Since signing research bilateral with U. S., we are not considering other two possible sources: Britain, Russia. | Again, solid yes. However some extreme nationalists on National Research Council voiced strong, uninformed opinions such as "Why should we import more costly fuels—let's use our own uranium"; and "We should insist on a breeder type so that Brazilian thorium can be used" (*sic*). |
| 3. | Cannot tell now: we don't know yet what direction our program will take, we are just starting to consider our power program. Obviously we would not like to be dependent permanently on outside supplies, so we plan to work not only with U but also with thorium (of which we have plenty) and breed $U^{233}$—a self-propagating system. | 1957: 1.5 kg for a water-boiler we hope to order from NAA within a few weeks for delivery in Feb. 1957 (negotiations are now going on in Tokyo). 1961: about 8 kg total—4 for a swimming pool for summer 1958 delivery, 2.5 for a CP-5 for winter 1958. 1966: about 18 kg total, including 10 for various reactors the government may import or manufacture in second 5 years. | At moment not possible to give concrete figures. | 1957: 6 kg, covered by research bilateral. Needs beyond that have not been determined. Depend on how much will be needed by American & Foreign Power Co. 10-Mw plant, if Brazil is to get one, and on whether other power companies set up nuclear plants. |
| 4. | Immaterial—only the terms and conditions matter. For a real power program, we would insist on buying. | Would prefer to buy, but will lease if necessary. | Choice cannot now be made. We would prefer to start by leasing because, lacking experience, we would prefer U. S. to take reprocessing risks. | Leasing, because . . . |
| 5. | Yes. We have no reprocessing plant at present, but we certainly will produce Pu and $U^{233}$. | Yes, we strongly want to do our own reprocessing. | In the future, yes. Having gained experience, we will want to reprocess in order to obtain valuable derivatives such as Pu and other fission products. | . . . Brazil not equipped to process at present. |
| 6. | We may as an interim arrangement but not for a long-range power program. | Yes, but reluctantly. | We are not in a position to answer now. Would accept U. S. reprocessing as a condition at the outset, in case of lease. Later, as U prices fall, we would not continue to accept this condition. | Yes. Already accepted under research bilateral. Will continue this policy until we can set up our own reprocessing plants, which won't be feasible for some time. |
| 7. | It depends on the reactor; our swimming pool needs high enrichment, say 20%. | 20% for research reactors, 2–10% for power reactors (first to be built about 1966). | Will depend on type of reactor. | Depends on requirements of power reactors that may be proposed. |
| 8. | Nothing specifically yet; our second reactor doesn't need it. We can't do more until our further program has been defined, and sale conditions better known. | Japan has a research bilateral and is conducting negotiations in Washington on details of lease arrangement. | We have signed research bilateral with U. S. | Research bilateral signed; also "certain military and top level agreements between U. S. and Brazil make the way much easier for imports of U to come from U. S. than any other country." |
| 9. | It is a very generous and imaginative offer that will help the development of atomic energy, on one condition: that inspection and safeguards are not made so heavy and discriminative between haves and have-nots as to make it difficult for countries to accept. | We appreciate the offer, but think the conditions are too strict. We want to buy rather than lease, because under the present proposal the U. S. would not be responsible for damage to the fuel element even if it is caused during processing in the U. S. | News chiefly interesting to countries lacking U resources. Argentina not only has natural U, but has recently bought a processing plant from Degussa-Leybold of Germany which uses high vacuum method to purify U. | A minority asks why U should be imported when we have it here under the ground. Britain was only other country that has shown any interest in eventually supplying us with atomic power or fuel; so far has offered only technical training: fuel and reactor offers have been "cautious and vague." |

§ . . . for limited experimental purposes, perhaps also for power provided new fuel bred in it is not subject to any restrictions.

## Thorough Review Sought Of Atomic Secrecy Policy

A call for a serious study and evaluation of our whole secrecy philosophy in atomic energy, was heard at an Atomic Industrial Forum meeting last month.

Addressing a session on "Public Relations for the Atomic Industry," Jerome D. Luntz, editor of NUCLEONICS, declared, "AEC does not seem to want—or to be constitutionally able—to resist the temptation to impose its imprint on the development of the nuclear industry . . . As far as information is concerned, AEC has cut out for itself the role of taking industry by the hand and giving it what information AEC feels it should have. This spoonfeeding or coddling has resulted in the massive access permit program that is growing by leaps and bounds and may have unrealized evils . . . The sensitivity of (this) confidential information is said to be such that if it were to be publicly disclosed it would not be particularly harmful to the country.

"I feel that the access permit program is being used as a political expedient in place of declassification, and that actually it is a poor substitute for declassification, because (a) newcomers may become too dependent on being spoonfed data, but I don't think AEC can possibly keep its fingers on the pulse of industry's information needs; (b) unless confidential information has a finite life, it may well become a burial ground for classified information. The incentive for declassification is gone. Many meetings are held on a classified basis now because it's easier to do it that way; (c) because of the mixture of secret, confidential, and unclassified information that many permit holders are exposed to, I submit that the security of our information is much looser today than it has ever been; (d) we'll certainly reach the point one day where very few people will not have access to U. S. classified information."

Governmental trade secrecy "is illegal under U. S. law and perhaps even unconstitutional," the speaker said, adding he was not criticizing trade secrecy—an important contributor to technological progress when used by industry. But, "apart from the question of the legality of the government's use of trade secrecy, the ultimate user of our own trade secrets, industry, is better able to judge what should and should not be withheld."

# About the Industry

**United Shoe Machinery Corp. enters field.** The Boston firm signed a $3-million contract with General Electric to develop, build and test reactor components for Knolls Atomic Power Lab. United's Atomic Power Dept. will operate a new testing laboratory at Beverly, Mass., to test control equipment under simulated operating conditions for the Submarine Advanced Reactor, which GE is developing at KAPL.

**So does Bell Aircraft Corp.** The Buffalo plane builder hired Stuart Mims from Westinghouse to head its new nuclear study group.

**Nineteen companies affiliate around test reactor.** With the nation's first reactor designed for industrial research ready to go critical this month at Armour Research Foundation's new $1.25-million research building in Chicago, 19 industrial firms* joined a cooperative three-year program to study the application of nuclear techniques to their industrial problems. Each firm is contributing $20,000 for the $700,000, 50-kw water-boiler built by Atomics International (NAA); ARF is picking up the rest of the tab. It will enable industry for the first time to conduct reactor studies without security restrictions and military competition, ARF says.

**General Atomic settles down.** General Dynamics has accepted from the city of San Diego a lease on about 300 acres in the Torrey Pines area as the site for its General Atomics division's basic nuclear research laboratory. The lab, main concern of the division at present, will concentrate initially on research leading to the development of more efficient reactor systems. Externally, the $10-million lab will resemble a college campus; Pereira & Luckman, architects for Caltech and other West Coast colleges as well as for the National Bureau of Standards laboratory at Boulder, Colo., have been retained to design the Torrey Pines facility.

**New U source.** Uranium-bearing lignite deposits in the western Dakotas are the object of a new collaboration between AEC and private industry. At present these uraniferous lignites cannot be treated economically using standard metallurgical techniques applied to rock ores. Considerable research has been done, AEC says, by National Lead Co. at the AEC-owned lab at Winchester, Mass., to develop an economic process to recover the U from lignite. Last month AEC concluded arrangements with a combine of the Ohio Oil Co. and Arthur E. Pew, Jr. of Philadelphia, assuring them that AEC stood ready to buy U concentrates produced from lignite. The Ohio Oil-Pew group will conclude development work in six months. They have retained Catalytic Construction Co. to build a privately-financed pilot plant at the Colorado School of Mines. If results are successful, Ohio Oil-Pew will get an AEC contract for U concentrates, and will build a full-scale mill to be in operation by the fall of 1957. AEC said the average U content of the Dakota lignite may be 0.2 to 0.4%; AEC's acceptability minimum is 0.1%. The project holds hope of doubling present domestic U output, making the U. S. independent of foreign U supply. Information developed by AEC is available to all groups interested in processing uraniferous lignites.

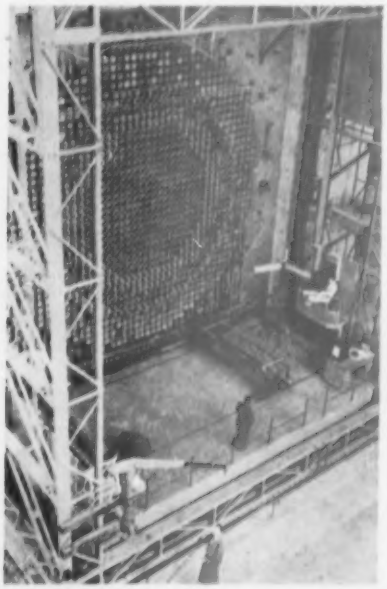
* Armour & Co., Chicago; Aro Equipment Corp., Bryan, O.; Ball Bros. Co., Muncie, Ind.; Borg-Warner Corp., Bellwood, Ill.; Clark Equipment Co., Buchanan, Mich.; Dewey & Almy Chemical Co., Cambridge, Mass.; Elgin National Watch Co., Elgin, Ill.; Eli Lilly & Co., Indianapolis; General Portland Cement Co., Chicago; Gustin-Bacon Mfg. Co., Kansas City; Illinois Tool Works, Chicago; Inland Steel Co., East Chicago, Ind.; M. W. Kellogg Co., New York; Kimberly-Clark Corp., Neenah, Wis.; Ohmite Mfg. Co., Chicago; Richardson Co., Melrose Park, Ill.; U. S. Steel Corp., Pittsburgh; Universal Oil Products Co., Des Plaines, Ill.; Victor Chemical Co., Chicago.

# Reactor News

**Component commitments for private fast breeder.** Note to pessimists who say the private reactor program is just a paper program: Detroit Edison's combine of firms planning a mostly-privately-financed fast breeder has ordered $2,355,010 worth of hardware, as follows: a pressure vessel and rotating plug from Combustion Engineering; a crane with offset fuel-element handling mechanism from General Electric; a primary shield tank from Chicago Bridge & Iron Co.; eight scram rods and two shim rods from Allis-Chalmers; a 16-in. stainless steel check valve from Edward Valves; a liquid-sodium piping system, including a design study and stress analyses of the sodium primary loop from M. W. Kellogg; a complete pump unit for liquid sodium from Byron Jackson Division of Borg-Warner; also architect-engineer services from Commonwealth Associates. The components will be assembled first as a full-scale non-nuclear test facility at Edison's Delray plant, slated to be ready early next year. After testing, the components will be reassembled at the reactor site at Lagoona Beach, Mich.

**Two new all-private schemes broached.** Two more plans for privately-financed power reactors brought the total in this category to five (Con Ed, Commonwealth, and Pennsylvania Power & Light are earlier entrants). Florida's three largest utilities, interconnected for years, combined to propose a nuclear power plant "to be located at an appropriate site within suitable transmission distance of all three companies." The service areas of the three converge at the Tampa Bay area. The companies are Florida Power & Light of Miami, Tampa Electric of Tampa, and Florida Power Corp. of St. Petersburg. Babcock & Wilcox will design and manufacture the nuclear plant; Allis-Chalmers will build the turbo-generator set. Stone & Webster will be architect-engineer. The plant's capacity of 200 Mw is the largest nuclear output yet proposed. Reactor type has not been decided; a solid-fuel, liquid-bismuth cooled graphite-moderated pile has been mentioned. The philosophy of the agreement parallels that of Penn. P. & L.: design will not be frozen until research studies indicate that the reactor type chosen will be economically competitive in the area. Florida Power spokesmen say the plant will be needed by 1962, because of the rising cost of fuel oil, used to make most of the state's power. Florida is one of the highest cost power areas in the country.

The second proposal was made by Pacific Gas & Electric Co. of San Francisco, one of the original study group companies in 1951, and General Electric. PG&E will install a 5-Mw turbogenerator to tap surplus heat from the boiling water reactor GE is building at its new Livermore, Calif., nuclear center as a pilot plant for the larger Commonwealth boiling water reactor (NU, March '56, p. 22). Like Southern California Edison's plan to tap the Sodium Reactor Experiment (NU, March '56, p. 24), the power will not be firm. Costs will run $3–4-million.



G-1, MARCOULE: The loading face

MARCOULE, GENERAL VIEW: G-1 is at the center

**Details on France's G-1.** The French Atomic Energy Commission furnished additional data to NUCLEONICS about its first power reactor, G-1, which went into operation earlier this year (NU, Feb. '56, p. 15). The open-cycle air-cooled pile has 1,337 horizontal fuel channels each containing two of the 2,674 uranium cartridges (100 tons U total); to make the latter, a special fuel-fabrication factory was built at Annecy. Another special shop was set up on the site at Marcoule to make the 16,000 moderator bricks ($10^{-4}$ mm tolerance) from 1,200 tons of graphite, which were refined to nuclear purity by a French process. Coolant air is filtered and cooled before it is pumped into the reactor at 550 lb/sec by three groups of blowers (there is a fourth for emergency). After leaving the heat exchanger, the air is filtered through glass-wool, then exhausted through a 325-ft stack. Regulating rods are of boron carbide. Instrumentation includes 72 circuits read in the 1,500 ft² control room on an 88-ft master panel alone, not counting auxiliaries. The control system automatically shuts down the pile in case of excess: reactivity, power level (measurable from 20 w to 50 Mw), activity of exit air, or temperature at any one of several thousand points inside the reactor.

# World News

**Ten reactor types to be built in Soviet 5-year plan.** Prof. Igor V. Kurchatov of the Soviet Academy of Science told the 20th Communist Party Congress in Moscow: "In order to obtain electricity, 1½ times more funds must still be invested in nuclear than in thermal plants. But the cost of electrical energy from atomic plants can now equal the cost of electricity from thermal plants.

"Two one-million-kw atomic power plants are to be built in the Ural Mts., and a 450,000-kw plant near Moscow; they will thus be greater than the atomic power plants planned in the U. S. and England. But these plants are still experimental ones and the point is to establish the range of atomic energy for the next 5-year plans. During this plan [1956–60] ten types of atomic reactors will be built . . . Atomic motors are also included in the 5-year plan. The technical design of an atomic ice-breaker that can stay at sea 2–3 years without refueling is being completed. This work should be extended to other types of ships and to aviation . . . By 1960 the Soviet will have radioisotopes equivalent to 10,000 tons of radium . . . A 10-Bev accelerator has been built and a 50-Bev accelerator is planned . . . "

**Predictions in Britain.** Sir John Cockcroft, director of British atomic research, says Britain's future nuclear power stations may have outputs of as much as 500 Mw each. This compares with 60-Mw (electric) at the experimental Calder Hall station, and 100–150 Mw at the first two power stations now about to be started. Sir John also estimates the weight of shielding for an airplane reactor at 100,000 lb—making the plane weigh over 200,000 lb. He said the principal problem in nuclear aircraft propulsion is to develop heat at a sufficiently high temperature for a gas turbine.

**Philippines get Asian research center.** Manila will be the site of a U. S.-financed nuclear research center for the Colombo Plan countries of southeast Asia—from Pakistan to Japan. Ceylon had been a strong contender for the site, and the U. S. made a separate, consolation offer of a research reactor to Colombo. The Philippines was said to have been selected for the regional center because of its combination of local educational and scientific facilities and easy communications with the rest of the area. First step toward setting up the center is the dispatch this month of a Brookhaven team headed by Marvin Fox (NU, Mar. '56, p. 24) to inspect facilities and site possibilities at Manila and to confer with participating countries on their interests, plans, and needs. The U. S. will contribute $20-million of the center's cost.

**Brazilian drops top job.** Glycon de Paiva Teixeira, named head of Brazil's AEC in the new Kubitschek regime (NU, Mar. '56, p. 23), officially refused the post. According to advices to NUCLEONICS from Rio, he felt the job less important, in view of Brazil's undeveloped atomic status, than his former post heading the Development Bank.

**Nuclear ship combine formed.** Three British firms have formed a new group to work on nuclear propulsion for ships: Vickers, Rolls-Royce, and Foster Wheeler Ltd. Rolls-Royce recently disclosed it had been working on aircraft nuclear propulsion for 18 months (NU, Mar. '56, p. 23).

**Ireland to get a U. S. reactor.** External Affairs Minister Liam Cosgrave told the Dail his government will accept the U. S. offer of a research reactor. He disclosed a bilateral agreement is under negotiation.

**Peaceful uses stressed in Israel.** Modern industrial methods based on harnessing nuclear energy are to be taught at the Technion—the Israel Institute of Technology at Haifa. The special course for practising engineers and management personnel is in addition to research and training facilities in pure and applied nuclear science. Also, Israel's AEC is being enlarged to include representation for the major higher education and research institutions as a deliberate emphasis of peaceful as against military uses of the atom. Latest project is for an atomic power plant to use uranium extracted from Negev desert phosphates.

**Baghdad regional center advances.** A group of atomic scientists of the Baghdad Pact countries and British experts from Harwell began a series of meetings in Baghdad to study establishment of the atomic training center that Britain will help found and equip (NU, Jan. '56, p. 15).

**Unesco aids Pakistan.** The U. N. Educational, Scientific and Cultural Organization will help Pakistan set up a nuclear physics department at the Federal University of Karachi, and is sending Frans Barendregt, chief scientist at the new Dutch Reactor Center at the Hague, on a teaching mission to Karachi for this purpose.

**Harwell spilling over.** Britain's atomic research establishment at Harwell, 50 miles west of London, is getting two annexes for its expanding work. An unused RAF field at Grove 6 miles away will house the Technological Irradiation Group, formed last year to aid industry to make full use of available radioisotopes; moving this group out of Harwell will cut red tape, make it easier for industry to use the irradiation facilities. The Isotope School will follow to Grove. And a 700-acre site at Winfrith Heath near Dorchester, Dorset, is being considered as a new research reactor site. In a staff reorganization anticipating this move, J. V. Dunworth, formerly head of the reactor physics division at Harwell, moves up to head a new reactor division including reactor engineering and engineering development as well as reactor physics.

**Colombia organizes.** The Colombian Institute for Nuclear Affairs has been founded by the Bogota government. It will develop a program for peaceful applications of atomic energy, train personnel, build reactors and promote radioisotope use.

**Japan plans atomic independence.** Yoshita Sasaki, head of the Atomic Energy Bureau, declared Japanese acceptance of U. S. uranium would be limited to the experimental stage of Japan's atomic power generation program. When practical nuclear generation of electricity starts, Tokyo plans to obtain the necessary raw materials from Japan's own natural-uranium resources and heavy-water production.

**Chile to exploit uranium.** The Chilean AEC is setting up a company to work 0.2–0.3% uranium ore deposits in the neighborhood of Copiapó. It is also studying the possibility of building a $36-million concentration plant for radioactive minerals. U. S., Canadian and German companies have offered economic aid.

**Australia sells uranium to U. K.** Australia's Mary Kathleen Uranium Ltd. contracted with Britain's Atomic Energy Authority for sale of $90-million worth of uranium oxide from the Mary Kathleen mine in northwest Queensland. A $22.4-million reduction plant is to be built there; production will begin in 1959. The value of the contract may even reach $135-million if ore reserves at the South Alligator River area of the Northern Territory are proved by 1958.

# ROUNDUP

## News in Brief

**JCAE finds a staff director.** James T. Ramsey, counsel and assistant to the manager of AEC's Chicago Operations Office, is the new executive director of the Joint Congressional Committee on Atomic Energy, succeeding Corbin Allardice who resigned last August. Ramey has been Chicago Operations counsel for ten years.

**Radiochemistry lab for NDA.** Nuclear Development Corp. of America last month began construction of a radiochemical laboratory building, second link in development of its nuclear experimental station at Pawling, N. Y. A critical facility is abuilding (NU, Feb. '56, p. 16). The hot lab's primary aim will be to study the effects of radiation on fuel elements and structural components of reactors by examining test specimens after irradiation.

**The atom in the South.** Two regional meetings on the outlook for atomic energy in the South and Southwest are being organized by the Atomic Industrial Forum, one in Atlanta and Oak Ridge this month, one in San Antonio next month. Both will review the latest developments and applications of special interest to the South, will point out opportunities for local industries and responsibilities facing local civic and educational leaders. A sizable delegation from Mexico is expected at the San Antonio meeting.

**Two more university accelerators.** Harvard and MIT jointly will build and own an 8-Bev proton accelerator, with AEC support. Princeton is planning a 3-Bev proton machine, likewise with some AEC research division money. Both projects have study groups already at work; the Cambridge group is understood to be further along. Both have submitted proposals to AEC.

**Report on heavy-water sales.** AEC disclosed 129 tons of $D_2O$ have been approved for sale to six nations—$7,224,000 worth at $28/lb. So far only 16 tons have actually been shipped abroad—11 to Britain, 5 to France. Total amounts approved for sale are: UK, 50 tons; France, 30; India, 21 (of which 10 was announced in Feb. 1955); Australia, 11; Italy, 10; Switzerland, 7.

**Third separation plant completed.** AEC's last new gaseous diffusion plant at Portsmouth, Ohio, has been placed in full operation several months ahead of time. Cost of the plant was $800-million, 32.5% under the original estimate of $1,219-million.

**U. N. begins radiation study.** Nuclear specialists from 15 nations—the scientific committee on the effects of atomic radiation—held their first session at U. N. headquarters in New York to plan an international radiological survey. C. E. Eddy of Australia was named chairman, Carlos Chagas of Brazil vice-chairman, and Gunnar Randers of Norway, atomic adviser to U. N. Secretary-General Hammarskjöld, secretary. The group was established by the General Assembly in December to analyze and collate reports by 85 nations on radiation levels and radiation effects "on man and his environment." Represented on the committee are Argentina, Australia, Belgium, Brazil, Britain, Canada, Czechoslovakia, Egypt, France, India, Japan, Mexico, Sweden, the United States and the USSR. The first session was marked by the same spirit of harmony and scientific dedication that characterized Geneva last year.

Seven working groups were set up: genetics, effects of internal, and of external radiation, natural radiation background, exposures during medical procedures, occupational exposure, and environmental contamination. The group recommended that continuing personal files be maintained for persons occupationally exposed to radiation, these files to include medical records. It also moved for a coordinated study of the total amount and distribution of fallout over the surface of the globe and the amount and composition of radioactivity still in the upper atmosphere, also studies on $Sr^{90}$ in food chains, and on ocean contamination. It asked each U.N. member nation to submit periodic radioactivity measurement reports.

**The declassification numbers game.** Having completed review of 30,773 "research and development reports and informal memoranda," AEC said 11,283 were retained under wraps—although of these only 5,700 had "primary relationship to military propulsion reactors or weapons"; 10,916 were declassified, and 8,574 were placed in the "confidential" gray area. Some observers contend that these reports and "informal memoranda" indiscriminately include hurriedly-done wartime papers now completely outdated that do not deserve being brought out in today's stage of development.

**Controlled fusion door opening to industry.** As of March 23, AEC had received 54 requests from industry for access to secret data on controlled thermonuclear reactions, had granted 29, was still processing the remainder. Many requests are from firms already holding an access permit. Rules for getting fusion information are no different from those for a score of other secret but nonmilitary categories set up by AEC; permit holders must show a "need to know" to get access.

**Insurance progress.** The Joint Congressional Committee on Atomic Energy called in representatives of AEC and equipment, utility, and insurance firms for a two-day roundtable on the problem of indemnification against reactor hazards. It was "a most constructive hearing," said JCAE chairman Senator Anderson, adding that "Committee action with a view to solving present problems would soon be forthcoming." Meanwhile two preliminary progress reports were filed by independent groups working on the problem. One, the AEC's 10-man insurance study group, indicated that although "substantial progress" had been made in dealing with the high limits of third-party liability being sought, the final answer to this problem is as distant as ever. The other, a $50,000 study of the legal problems of insuring atomic power plants commissioned by the Atomic Industrial Forum at Columbia University Law School, is much more detailed, although also a provisional report. It finds that "the aim of the government should be to place a ceiling on the amount of liability for which the reactor industry must provide through normal channels and, in that area, let risks be carried or insured as individuals see fit, subject, however, to a requirement that the public be adequately protected. . . . Whether the ceiling should be at the same level for all reactors is a question which requires careful study." It also points out the word "insurance" is inadequate as used in this context; it restricts its use to coverage which the insurance industry can provide, and calls "indemnity" a government program of excess coverage on losses "not reasonably expectable and recurring."

**New operator at U mill.** National Lead Co. was named by AEC to take over operation of its uranium processing mill at Monticello, Utah. Galigher Co., which ran the mill for AEC since full-scale operations began in 1949, withdrew. Monticello has often been used as a yardstick to determine the profit margin of private millers.

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## model 2603

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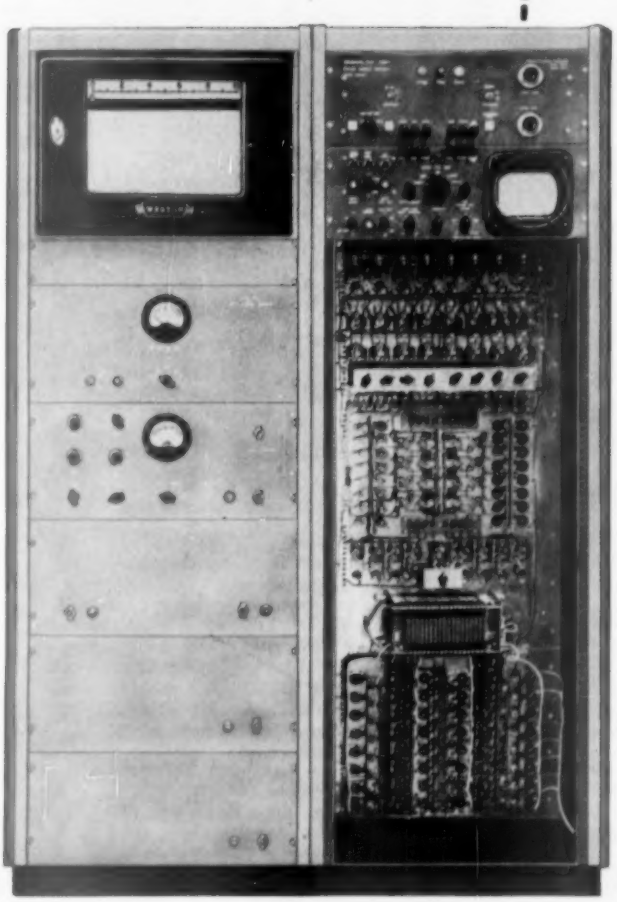

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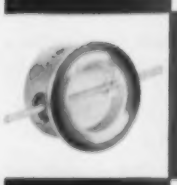

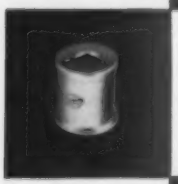

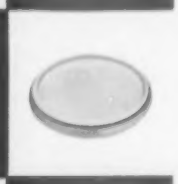

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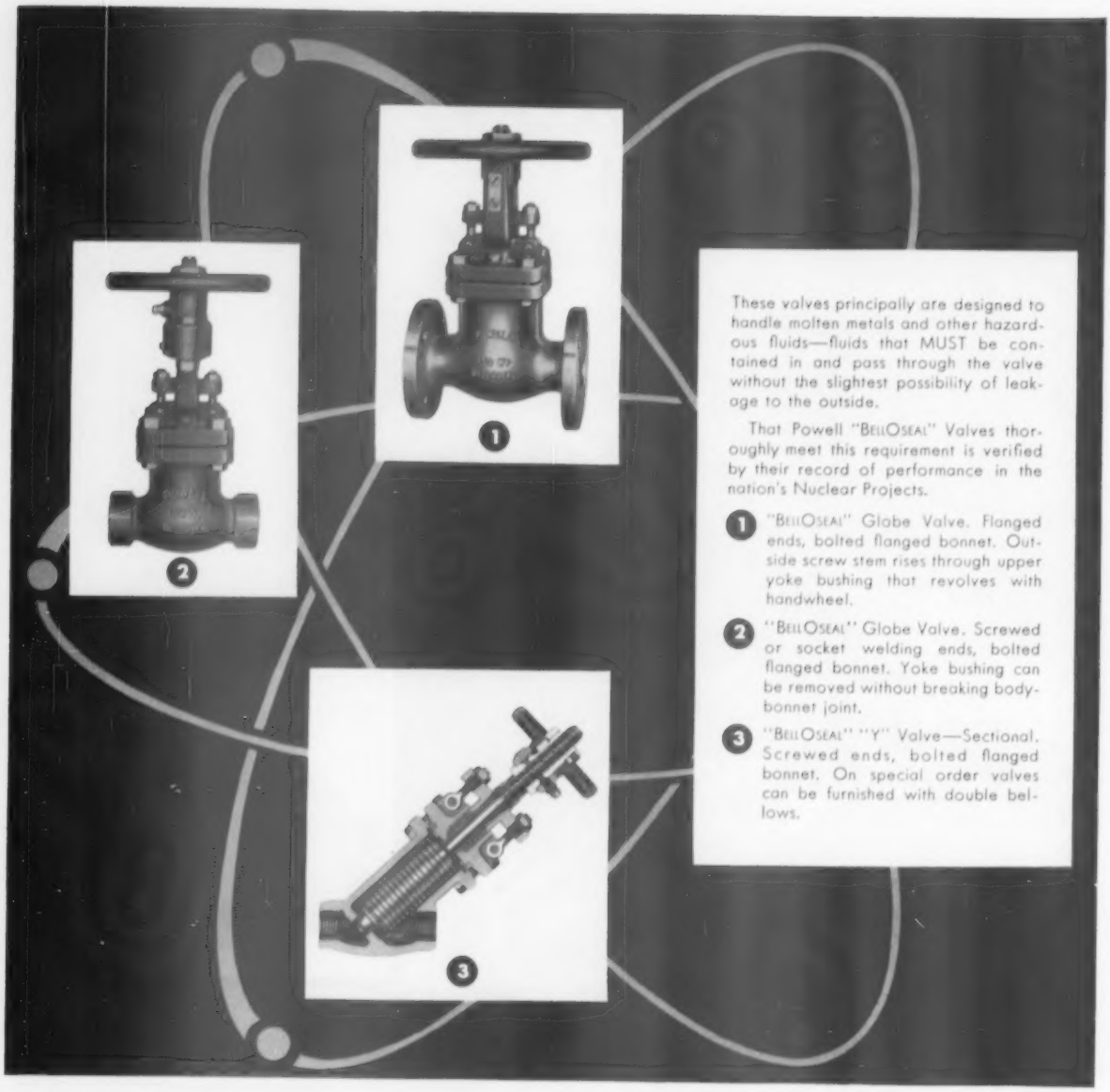

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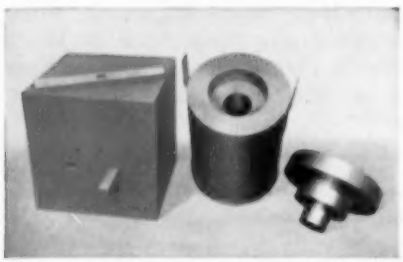

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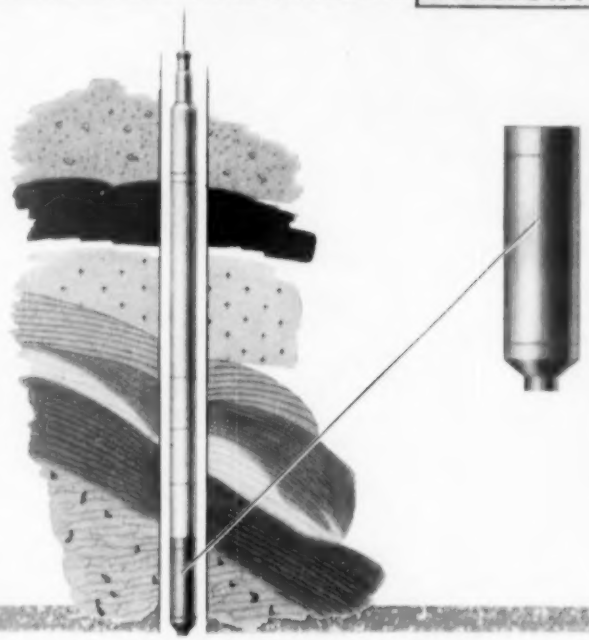

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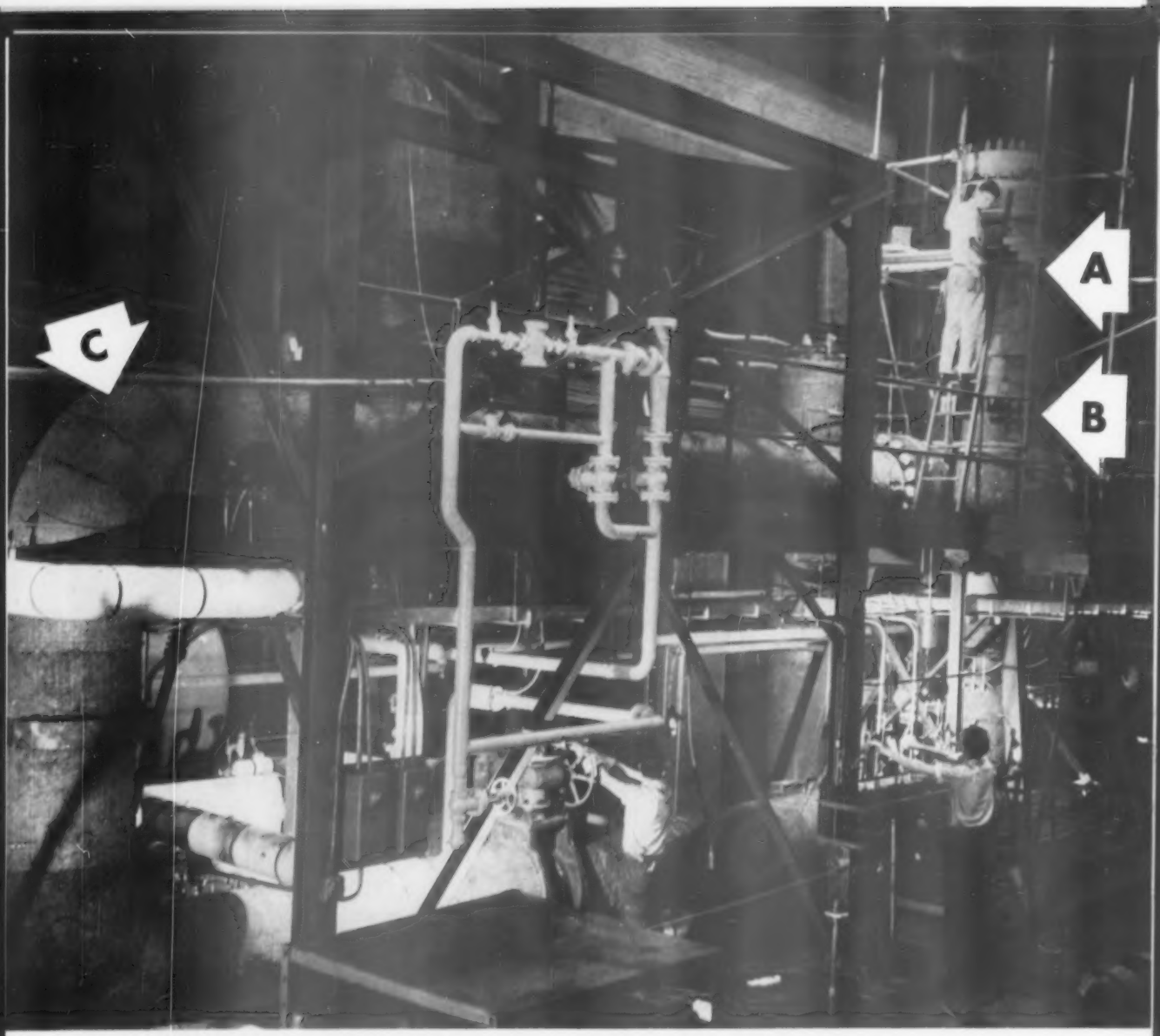


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# Scintillation Counting —1956

With this special report, NUCLEONICS again brings you abreast of current developments in scintillation counting.

Many developments reported on at length at this year's Scintillation Counting Symposium were only hopeful ideas at the conference two years ago. (See special report in March, 1954 NUCLEONICS.) Gaseous scintillation counting (p. 34) is now an accepted, if novel, laboratory tool that provides for very fast particle detection with extremely low sensitivity to gamma rays. As an outgrowth of counting in noble gases, liquid and even solid xenon look interesting as fast, efficient, high-atomic-number, but expensive detectors (p. 37).

The new high-output photomultipliers are coming into use (p. 54) and the old ones are being made better. Millimicrosecond electronics is now a highly developed art (p. 56) and every source of pulse width is being eliminated (p. 45).

People are taking a long hard look at the sources of the relatively poor pulse-height resolution of scintillators (p. 53).

The application of all these new elements has made possible a vast armory of neutron detectors (p. 38). It has brought scintillation counting into a medical application where every source of background must be eliminated (p. 40). Pulse height analyzers are made more important by the broadened use of fast linear scintillation counters; W. A. Higinbotham reviews the present situation on p. 60.

These articles are all based on papers delivered at the 5th Scintillation Counter Symposium held in Washington, February 28 and 29th. The editors are indebted to the officers of the symposium for their help. The complete versions of all papers will appear in the Transactions on Nuclear Science of the IRE.

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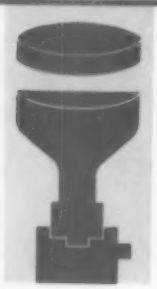
*Scintillators* **page 48**

*Photomultipliers* **page 54**

*Electronics* **page 56**



Counters

# Gaseous Scintillation Counting

**Faster pulses and almost complete insensitivity to gamma rays are the prime virtues of new schemes for detecting the passage of charged particles through gases**

By C. EGGLER and C. M. HUDDLESTON
*Argonne National Laboratory,* Lemont, Illinois*

Basically gaseous scintillation counting (*1*) involves detecting the light emitted by gas molecules ionized and excited by the passage of a charged particle. The light emitted should be proportional to the energy expended by the charged particles. The scintillation light pulses, this light of de-excitation, could then be collected and analyzed by a differential discriminator.

The first attempt to make a noble-gas scintillation counter was by Carl Muehlhause (*2*) in 1953. He found a barely detectable light output from argon and from helium when those gases were excited by Pu alpha particles. He found no advantage in using stilbene or NaI as a wavelength shifter for the conversion of ultraviolet light into the region of photocathode sensitivity of his 5819 photomultiplier tube.

Slightly later, Wiegand and Segrè (*3*) showed that the light output of the argon counter increased with an electric field. In that case, the cell was operating as a proportional counter except that it was light rather than electrons that was used to measure the event. Even so, the speed of the counter was limited by the time required for electron collection, of the order of microseconds.

Our first satisfactory gas cell was a 2-in. aluminum hemisphere like that in Fig. 1. An alpha source was located on the inside, and the cell was filled to a pressure of 5 atmospheres of argon. At one end of the cylinder were a Pyrex window and a photomultiplier. The inside of the window was coated with a thin layer of tetraphenylbutadiene in polystyrene. This plastic converted ultraviolet light into the visible region. The inside walls of the gas cell were also coated with a layer of the color shifter over a silvered or aluminized reflector.

With this arrangement a resolution of 15% was obtained for 5.47-Mev $Pu^{238}$ alpha particles. The rise time of the pulses was about $10^{-8}$ sec. The counter was notably insensitive to gamma rays.

## Mechanism

Although our understanding of the mechanism is not clear, some general considerations will be presented here. Heavy nonrelativistic charged particles lose energy primarily by excitation and ionization of atoms in the stopping gas (*4*). The cross sections for the excitation processes are not known quantitatively, but work on this point is being done at Columbia (*5*).

When an alpha particle passes through argon gas, then, it leaves in its wake argon atoms that may be

## Gas Cells Plus Photoconductors . . . . . Slower, but More Sensitive

*If one is willing to sacrifice speed for sensitivity, there may be better ways to use a scintillating gas than in conjunction with a photomultiplier tube.*

*A cylindrical gas cell 2 in. in diameter and 2 in. high was filled to a pressure of 3 atmospheres of argon. A PbS photoconductor (16) measuring 2 × 2 cm was located far enough from an alpha source that alpha particles were stopped in the gas before reaching it. Differential analysis of the pulses gave a resolution of 30% for a solid angle of 5%. The PbS must be responding to red or infrared radiation because the plastic color shifter does not appreciably affect the response of the photoconductor. Also it has been noted that neon works well with PbS, whereas neon was the only noble gas that never worked well in any other type of gas scintillation counter.*

*Experiments are now in progress to improve the solid angle by using several small photoconductors. Noise can be suppressed by requiring coincidence between two portions of the photoconducting envelope.*

* Work performed under the auspices of the U. S. Atomic Energy Commission.

ionized, excited, or both ionized and excited. Each excited atom or ion returns to its ground state with the emission of one or more photons of light within $\sim 10^{-9}$ sec, giving rise to a fast light pulse.

Ionized atoms also recombine to form neutral atoms with the emission of light, but this recombination light is emitted over too long a period to give rise to a sharp pulse. Similarly, resonance radiation, which will be trapped in the gas, is lost as far as fast pulses are concerned (*6*). Primary excitation to metastable states will presumably contribute nothing since the radiating states produced by collision with normal gas atoms will emit resonance radiation.

## Intensity Problems

Low intensity is a drawback that is not easily surmounted. One starts with photons in the gas cell and wishes to convert them into photoelectrons leaving the cathode of the photomultiplier tube. In this process of conversion, there are losses due to geometrical factors, reflection, transmission, wavelength shifting, and efficiency of the photocathode. The total number of photons available is about $10^5$/Mev. The efficiency of the photocathode and geometrical factors can easily reduce this number by a factor of 100. Other losses can account for another factor of 10, so that a 5-Mev alpha results in the emission of about 500 photoelectrons from the cathode of the photomultiplier. This would give a statistical resolution width of about 10%.

These losses must be cut to get a gas scintillation spectrometer with high resolution at energies of the order of 1 Mev. The best we have been able to achieve to date is a resolution of 10% at 5 Mev. There is need for improvement in this respect.

## How To Beat Quenching

Pulse heights grow smaller with time. We believe this effect is due to the accumulation of noxious vapors from outgassing of the plastic color shifter. There are ways of overcoming this problem: cooling the cell, flowing the gas, continuously purifying the gas, or interposing some quartz between the gas and the plastic. Any of these methods can be used to get a stable counter.

**Use nitrogen.** One way of overcoming the quenching by poison is, clearly, to have a color shifter that does not give out a poisoning vapor. Such a shifter has been found in nitrogen, which, apparently, converts the argon (or helium) ultraviolet radiation into the visible region when the two gases are mixed in the proper proportions.

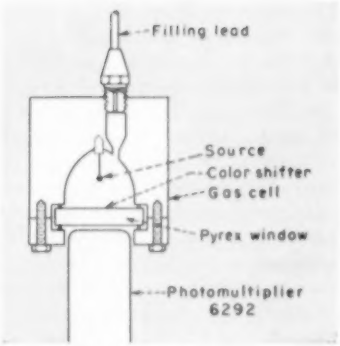



FIG. 1. Gas scintillation counter. Aluminum walls of gas cell are also coated with color shifter

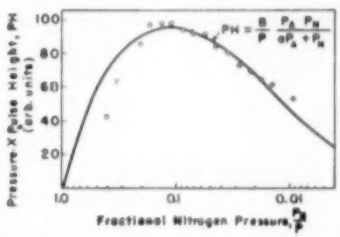



FIG. 2. Pulse height times total pressure as a function of nitrogen concentration. Data for one particular run are shown together with plot of semi-empirical formula with parameters $a$ and $B$ determined from many experimental curves

Figure 2 shows photomultiplier output pulse height as a function of nitrogen concentration at a fixed total pressure of 100 lbs/in$^2$. The exciting charged particles were 5-Mev alpha particles. When helium is used instead of argon, the optimum amount of nitrogen is less by a factor of the order of 100.

From the data of Fig. 2 and from other data at different total pressures and concentrations, one finds, to a good approximation

$$(P_A + P_N)\, H = B\, \frac{P_A}{(P_A + P_N)} \left[\frac{P_N}{aP_A + P_N}\right],$$

where $H$ is pulse height in volts, $P_N$ and $P_A$ are the partial pressures of nitrogen and argon in the gas mixture, $a$ is a dimensionless constant having a value of about 0.015,* and $B$ is a constant depending on the geometry, amplification and photocathode sensitivity.

In the above expression for $H$, the term $P_A/(P_A + P_N)$ simply says that the intensity of the initial ultraviolet light depends on the concentration of argon in the gas mixture. The bracketed term is typical of a competitive process where two alternatives are possible. Also it is seen that there is an inverse dependence of $H$ on the total pressure. We do not understand why this should be so.

Although the mechanism is not thoroughly understood, it appears that the argon is excited by the alpha particles. It further appears that either the excitation can be lost by interaction of the excited argon atom with another argon atom or can be converted into visible light by interaction of the excited argon atom with an $N_2$ molecule.

It is interesting to note that the ultraviolet light is apparently not the same as that described by Colli (*7*) and by Phelps and Molnar (*8*), where three-body argon collisions are involved, for, if it were, the $P_A$ in the bracketed term would be squared. Collisions between two metastable atoms (*9*) could possibly be important in determining the amount of light effectively lost.

There is yet another way to avoid the poisoning by vapor, and that is not to use any color shifter. If one uses an EMI tube with a quartz envelope and looks at the primary ultraviolet light through a quartz or LiF window, one sees light pulses. A resolution of 30% for 5-Mev alpha-particles is easily obtained in this manner. In this case there is negligible dependence of the pulse height on the gas pressure when either argon or krypton is used as the counter gas.

## Many Groups Using It

The gas scintillation technique, with various modifications, has been used by several workers. Boicourt and Brolley (*10*) have used krypton and tetraphenylbutadiene to study the

* Recent work indicates that $a$ depends on the purity of gases used. For very pure gases, the mixture for greatest pulse height is about 50% $N_2$. This is fortunate because the greater the concentration of nitrogen, the faster the pulses. The pulses have a duration of $\sim$30 m$\mu$sec at 10% $N_2$ and a duration of $\sim$8 m$\mu$sec at 50% $N_2$.

fission-fragment spectrum of $U^{235}$ induced by thermal neutrons. They report pulses that rise in less than $10^{-8}$ sec and a width at half-maximum of $2\text{-}3 \times 10^{-8}$ sec. One could not reasonably expect a pulse faster than that, because the alpha-particle requires about $10^{-8}$ sec to be brought to rest in the gas.

Nobles, Henkle and Smith (*11*) studied the excitation curve for neutron-induced fission of $Am^{241}$ using xenon as a counter gas and quaterphenyl as a color shifter. The fast response of the gas cell was particularly useful to them because the multiple pile-up of alpha particles from $Am^{241}$ ($10^8$ dps/mg) in a slower counter would obscure the pulses from fission.

Villaire and Wouters (*12*) used a flow counter to avoid poisoning by vapor from the plastic in a study of fission fragments from uranium.

A. B. Smith (*13*) is using an argon-nitrogen counter to measure the promptness of fission gamma-rays. The gas scintillator detects the fission event, and a conventional crystal counter detects the gamma-rays. The scintillations are so fast that he can measure exceedingly small delay times. He reports remarkable stability for his counter.

P. Hubert, L. Bollinger, and G. Thomas (*14*) are using an argon-nitrogen counter to look at fission fragments from $Pu^{239}$. They expect to be able to measure $\eta$ as a function of neutron energy. Hughes and Palevsky (*15*) are using a gas in a fission detector.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# Los Alamos Gas Counters


By JOHN A. NORTHROP and RALPH NOBLES

*Los Alamos Scientific Laboratory*
*University of California, Los Alamos, New Mexico*


Gas scintillation counters, particularly xenon counters, look very promising. Our results show that the contamination problem can be met by continuous gas purification, that gaseous scintillators are linear with energy, and that they are fast and efficient. Liquefied or frozen noble gases also show promise as fast dense counters.

One of the first things we did was to build a gas purifier, having recognized from the prior experience of others that the continual decrease in light output was probably caused by contamination with small amounts of gas given off by the gaskets and counter walls. Our gas purifier consists of a metal bellows and check-valve system to provide unidirectional flow through a furnace containing uranium turnings heated to 800° C, into a second section containing cold uranium (for hydrogen absorption), then to the counter and back to the pump. This system has produced large light pulses in the gas scintillator.

## Contaminant Effects

To assay contaminant effects, the change in pulse height was measured for several contaminant-Xe mixtures. Results for $H_2$ and $N_2$ are shown in Fig. 1. Oxygen and methane were worse; 2 and 4%, respectively, reduced pulse height a factor of six. Circulating the gas mixtures through the purifier restored the pulse heights to those with pure Xe. However, the reaction with $N_2$ was particularly slow, taking about an hour.

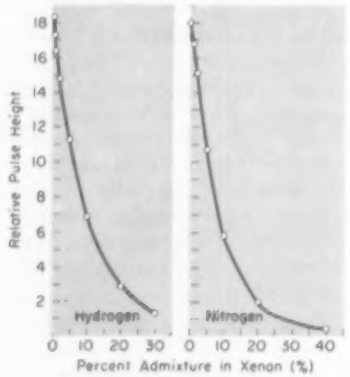


FIG. 1. Effect of contaminant gases on gas-counter pulse height. None of these are as bad as contamination coming from cylinder walls, which, in amounts too small to register a pressure change, can completely destroy light output

For possible use as a neutron recoil counter, it may be noted that as much as 10% $H_2$ can be introduced and still obtain usable light. Furthermore, at this percentage admixture, there was no measurable reduction in light collected as the total pressure was increased from 20 to 200 cm. An extrapolation of this result would indicate that rather high pressure systems might be used for neutron detection. The high stopping power of Xe would be useful in reducing wall effects.

## Waveshifters

The conventional method of applying the waveshifter to the phototube and cylinder walls by painting with a solution of it in some binder would not seem to provide complete coverage. Photomicrographs confirm this. We used vacuum evaporation to apply pure, uniform layers of known thickness of both quaterphenyl and tetraphenylbutadiene to both tube faces and counter walls. The pulse height obtained relative to thickness on the tube face is shown in Fig. 2. Although the tetraphenylbutadiene appears about one-third more efficient, it has the dis-

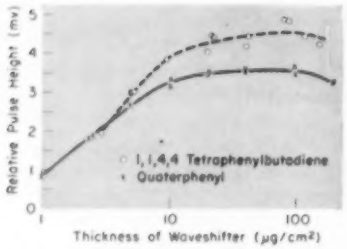


FIG. 2. Pulse height as a function of waveshifter thickness

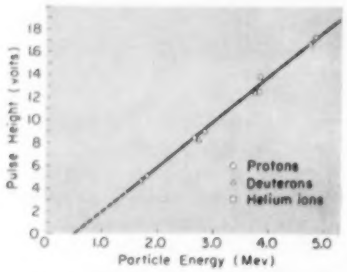


FIG. 3. Experiments prove gas scintillation counters linear; 0.5-Mev intercept is not understood

advantage of deteriorating somewhat with time. Thus, quaterphenyl was used for all subsequent measurements.

## Reflecting Systems

The cylinder was machined of Dural without polishing. Coating the cylinder walls with either smoked MgO or quaterphenyl doubled the amount of light obtained with just the tube coated. A coating of MgO followed by evaporated quaterphenyl was even more effective, giving five times as much light.

The efficiency of such a reflector system is illustrated by the following observation. The pulse height decreases only 9% as the Xe pressure is increased from 20 cm, at which pressure the $\alpha$-particles travel the length of the cylinder and stop just at the tube face, to 120 cm, at which pressure the light source is located at the opposite end of the cylinder. This decrease can be ascribed entirely to increased loss in the collimator at the higher pressure. Thus the MgO-quaterphenyl surface itself must have at least 90% reflection efficiency.

We compared several noble gases in this geometry. We also tested NaI using MgO but no waveshifter. The relative light outputs were NaI(Tl):Xe:Kr:A:Ne:He = 72:32:16:5:1:10.

Huddleston reports increased light output using certain gas mixtures, in particular, small amounts of nitrogen added to helium. We did not observe this effect in our light system. Admixtures of from 1 ppm to 10% were used. Up to 50 ppm there was no observed change in light output; for larger quantities the light decreased monotonically. It may be that nitrogen acts as a waveshifter only in those systems that do not otherwise have an efficient waveshifter-reflector arrangement.

Various mixtures of Xe in Kr, Kr in A, and Xe in He were tried in an attempt to increase the light output. The only mixture we found that appeared to be of much interest was 90% He 10% Xe, which gives as much, or slightly more, light output than pure Xe. The application to a $He^3$ neutron spectrometer is obvious.

## Energy Linearity

To check the linearity of a pure Xe counter for protons, deuterons, and helium ions of different energies, appropriate charged particles from the large Van de Graaff were elastically scattered by a thin gold foil through a nickel window into a counter filled with enough Xenon to stop the particles. Figure 3 shows that all the points fall quite accurately on a straight line and that different particles of the same energy give very nearly the same light outputs. The fact that the straight line extrapolates to an intercept of about 0.5 Mev is disturbing, to say the least. This may very likely be caused by some systematic error that was hard to locate, such as some inefficiency in light collection, rather than by any true nonlinearity in the scintillation process itself.

## Liquid and Solid Xe

Just recently we have been taking a very preliminary look at the scintillator system shown at the right in Fig. 4. Xenon can be liquified or frozen in the small cup below the phototube, which contains a small $\alpha$-source at the bottom. The reflector system is far from optimum, consisting of unpolished evaporated aluminum coated with evaporated quaterphenyl. A preliminary run on this shows that liquid and solid xenon have of the order of twice the light output of gaseous xenon, and thus would be comparable to NaI. The advantages solid xenon would have over sodium iodide are obvious. It has comparable $Z$, comparable density, is much faster and, at $15/liquid cm³, is not prohibitively expensive for many applications. Also, in the solid state it is not likely to be troubled by contamination poisoning.

A very preliminary look at the light output from liquid and solid Kr and A shows them to be comparable with Xe. This is unlike the gaseous state where the lower-$Z$ noble gases give smaller pulse heights.

All the liquids and solids observed are fast—decay times are under 10 m$\mu$sec. This contrasts with the gases for which decay time varies inversely with pressure and is roughly 75 m$\mu$sec at 25 cm, 30 at 50, and 14 m$\mu$sec at 100 cm.

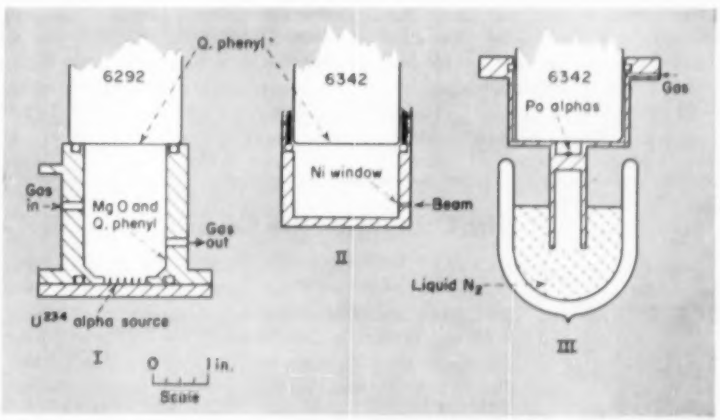


FIG. 4. First counter was used for alpha-particle measurements and studies of gas mixtures; second was used in linearity measurements; third is used to study liquid and solid Xe scintillators

# Neutron Scintillation Counters

By C. O. MUEHLHAUSE
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THE TABLE enumerates existing types of neutron scintillation counters and compares their principal characteristics. It is divided into columns that give: type (material phase), nuclear host (component effective in the primary nuclear reaction), atomic host (component in which the primary atomic or molecular energy is generated), scintillator (the light emitter), and other parameters.

Pulse-height dispersion is not included as it can be estimated from the pulse height, homogeneity of the scintillator, and the photomultiplier response. Similarly, the time dispersion can be estimated from these same parameters plus the time response and the imposed electronic resolving time. The final time dispersion or jitter depends in general on other factors of the over-all system as well, e.g. energy and time spread in the source.

## Speculative Counters

Speculative cases are indicated by bracketing the "nuclear host." These will be discussed in detail since they are not covered in the literature.

**Hydrogen gas counter.** A hydrogen-gas scintillation counter along the same lines used for the noble gases (p. 34) would be very useful for neutrons down to ~20 kev. Its good pulse-height response and low atomic number would be favorable in improving the signal-to-background ratio at all energies. Such a counter would be gamma sensitive primarily through Compton scattering by the walls of the cell containing the gas.

The microwave-powered vacuum ultraviolet spectrum of hydrogen clearly shows numerous sharp lines in the 1,000-Å region. The standard wavelength shifter used by vacuum-ultraviolet spectroscopists is sodium salicylate. The speed of this substance is unknown, but it has the approximately constant quantum efficiency of one-half for converting short wavelengths into violet.

**Lithium hydride.** Langsdorf of Argonne has suggested that LiH, being alkali-halide-like, might make a good scintillator if purified and activated properly. It would certainly possess admirable qualities as a neutron detector, namely: (a) detection of neutrons via hydrogen scattering would be possible; (b) the low-atomic-number material would result in depressed $\gamma$-ray sensitivity; and (c) neutron detection via lithium capture also would be possible. Regarding this last point a sufficiently large mass of this substance would again make it possible to discriminate against $\gamma$-rays by observing the double pulsing that results from the scattering-aging-capture process. Furthermore, the integrated light output from the proton recoils would be a direct measure of the neutron energy (*10*) provided the pulse-height response of the crystal is a linear function of proton energy.

## Counting Philosophy

- *Neutron research at all energies is preferably accomplished by determining a velocity (this includes crystal diffraction). A time-of-flight technique only uses the decay time of the crystal as a time marker, whereas an absorption technique is limited by the statistics of the crystal's pulse-height response. However, good pulse-height resolution is always useful in reducing background and there will always be many situations in which it is not feasible to pulse the neutron flux.*
- *Detection apparatus is growing in size and subtlety, and to some extent balances the emphasis on generators. The latest neutrino counters reported by Reines and Cowan fill a large room. Expensive counter arrays are often required to fully benefit from the capabilities of costly accelerators.*

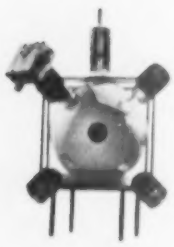
## Existing Counters

Space does not permit a full discussion of all the existing counter types listed in the table, but some features of two of them will be discussed here.

**Organic-liquid counters.** These demonstrate the three essentially different means of neutron detection: scattering, capture, and scattering plus capture.

When no neutron-capturing material such as B or Cd is added to the counter, detection is effected by hydrogen scattering, which gives rise to proton recoils. The pulse-height response to these particles is poor, thereby restricting the detection range to neutrons of $\gtrsim$500 kev. The sensitivity to $\gamma$-rays is of the order of a few percent per centimeter thickness of counter material. This may result in a prohibitively high background for steady sources. For pulsed sources, $\gamma$-rays originating in the same burst as the neutrons arrive at the detector much sooner than do the neutrons. This makes it possible to separate them by time-of-flight,

## The Counter on the Cover . . .



*. . . is an early version by the author of what is now regarded as a baby counter. The counter is shown while still under construction. Eight 2-in.-diameter photomultipliers view a 1-ft-diameter (12-l) Pyrex flask painted on the exterior with white Tygon paint and filled in the interior with the toluene-borate recipe. About 35% of the light generated is collected. The counter operates successfully in a 0.1-mr/hr $\gamma$-field for neutrons of ~3 Mev or greater. The design is undersize. (Cover photo by John F. Garfield, BNL.)*

thus giving low effective background.

A boron-loaded counter (*3*) operating as a simple neutron-capture device has a high efficiency for neutron energies below ~50 kev. If the counter is relatively large and composed 50% by volume of enriched methyl borate, the mean time, $\tau$, for capture to take place is ~0.4 $\mu$s. This can be approximately calculated from the mean life, $\tau_\infty$, for survival in an infinite $1/v$ capturing medium and the meanlife, $\tau_e$, for escape

$$\frac{1}{\tau} = \frac{1}{\tau_\infty} + \frac{1}{\tau_e}$$

Again the background is low only if the $\gamma$-rays are pulsed along with the neutrons.

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## Neutron Scintillation Counters

| Type | Composition: Nuclear host | Composition: Atomic host | Composition: Scintillator | Composition: Shifter | Nuclear reaction | Sensitivity: Neutron energy (kev) | Sensitivity: $\gamma$-ray | Pulse height relative to NaI(Tl) | Time response ($\mu$sec) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Noble gas | [$He^3$] | $He^3$+Xe | Xe | Quaterphenyl | $He^3(n,p)$ | < 500 | Low | 1/2 | 0.002 | 2 |
| | $B^{10}$ | Xe | Xe | Quaterphenyl | $B^{10}(n,\alpha)$ | < 10 | Low | 1/2 | 0.002 | |
| | $U^{235}$ | Xe | Xe | Quaterphenyl | $U^{235}(n,f)$ | < 10 | Low | 1/2 | 0.002 | |
| Diatomic gas | [$H_2$] | $H_2$+? | ? | Sodium salicylate | $H(n,n)$ | > 20 | Low | ~1/2 | 0.002 | |
| Organic liquid | Toluene | Toluene | PPO | POPOP | $H(n,n)$ | > 500 | High† | ~1/100 | 0.002 | |
| | Triethylbenzene + methyl borate | Triethyl benzene | PPO | POPOP | $B^{10}(n,\alpha)$ | < 50 | High† | 1/100 | 0.5 | 3 |
| | or cadmium octoate | Triethyl benzene | PPO | POPOP | $H(n,n)H$+ $Cd^{113}(n,\gamma)$ | >1000 | Low | 1/100 | 0.002 | 5 |
| Organic solid | Anthracene | Anthracene | Anthracene | None | $H(n,n)$ | > 100 | High-low†† | ~1/20 | 0.03 | 6 |
| | Polystyrene or polyvinyltoluene | Plastic | *p*-terphenyl | Tetraphenyl butadiene | $H(n,n)$ | > 300 | High† | ~1/50 | 0.003 | 7 |
| Inorganic solid | $Li^6I$ | LiI | Eu | None | $Li^6(n,\alpha)$ | < 50 | High† | 1/3 | 2 | 8 |
| | [$Li^6H$] | LiH | ? | None | $H(n,n)$ + $Li^6(n,\alpha)$ | > 100 | Low | ~1/2 | 1 | 10 |
| | $B_2{}^{10}O_3$ | ZnS | Ag | None | $B^{10}(n,\alpha)$ | < 10 | Low | $\lesssim$1 | 0.2 | 11 |
| | Lucite + ZnS | ZnS | Ag | None | $H(n,n)$ or $S(n,p)$ | > 100 | Low | $\lesssim$1 | 0.2 | |
| | $B^{10}$ | NaI | Tl | None | $Li^{7*}(\gamma)Li^7$ | <1000 | High† | 1 | 0.2 | |

† High with a random source, but low with a pulsed source that permits time-of-flight analysis.
†† High with large volume, but low with small volume.

# Reduction of NaI Background

By C. E. MILLER, L. D. MARINELLI, R. E. ROWLAND, and J. E. ROSE
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TO DEVELOP an apparatus capable of measuring the natural gamma radioactivity of the human body, our group has spent considerable effort in reducing the background counting rate of several scintillation crystals. Since this type of low-level counting is useful in many fields, we're reporting some of our experiences in detail.

## Main Shield

To shield both instrument and subject from the gamma activity emitted by ordinary building materials, we built an 8- × 8- × 6-ft room with 8-in. steel walls. See Fig. 1.

This type of construction has several advantages, most prominent being low cost, ease of assembly, and the possibility of recovering most of the material in it should its use be discontinued.

The gamma-ray background of a 1½- × 1-in. NaI(Tl) crystal was examined within this room as the steel plates were being laid on the frame. Differential pulse-height spectra, covering the range from 0.2 to 2.5 Mev, were obtained with 0, ¾, 1½, 3, 6 and 8 in. of steel in place. Figure 2 shows the spectra with and without a 6-in. iron shield. After the room was completed, the analyzer was recalibrated to cover the energy range from 70 kev to 2.5 Mev and runs were made inside the room with additional lead and triple-distilled-Hg shielding around the crystal. The data are summarized in Table 1.

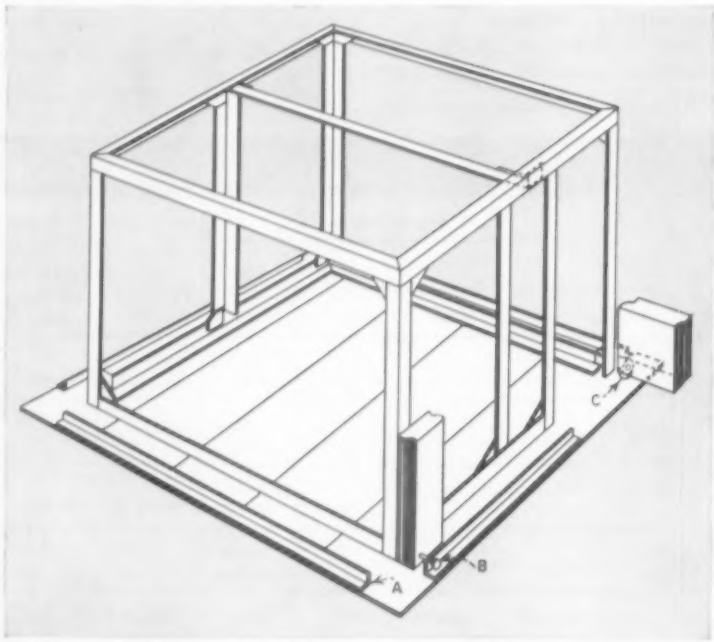


FIG. 1. Main shield consists of a bolted frame of 3½-in. angle beams upon which ¼-in. plates of 12-, 24- and 26-in. width were placed in staggered sequence on all sides to avoid continuous cracks. Two men handling up to 160 lb can assemble any thickness of wall desired. Floor and ceiling plates were simply laid in place; side plates were clamped together between frame and appropriately placed angle irons, A, by lag bolts, B. Access to room is by door swinging on roller bearings C and consisting of a welded steel box 6¾ in. × 2 ft × 6½ ft made and filled with ¼-in. plates. Although weighing 1 ton, door can be opened with only slight effort. The room weighs 52 tons and can be assembled by four men in two days

**TABLE 1—Effect of Shielding on Gamma-Ray Background**

| *Shielding (in. steel)* | *Integral background (cpm)* | |
|---|---|---|
| | *0.2–2.5 Mev* | *70 kev–2.5 Mev* |
| None | 576.4 | |
| ¾ | 312.2 | |
| 1½ | 173.2 | |
| 3 | 84.2 | |
| 6 | 46.6 | |
| 8 | 41 | 62 |
| 8 + 2 in. Pb | 29.5 | 41 |
| 8 + 1 in. Hg | 26 | 35 |
| 8 + 2 in. Pb + 1 in. Hg | 25 | 32.5 |

Note that the gross background (from 70 kev to 2.5 Mev) was never sensibly reduced regardless of the amount of shielding added beyond a thickness of 8 in. steel plus 1 in. of Hg. These thicknesses are sufficient to effectively eliminate the influence of local activity.

An estimate of the contribution from cosmic rays was made by placing a bank of cosmic-ray-sensitive G-M counters around the Hg shield and by measuring the coincidence rate between them and the crystal. The result, 7 cpm, is consistent with the cross sectional area of the crystal and the primary cosmic ray flux at sea level.

Attempts were made to determine the sources of the remaining 25 cpm, which were assumed to be inherent to the detector. Since placing another 5819 photomultiplier in front of the crystal added 7–10 cpm to the background, discarded phototubes were crushed and placed on the crystal. Activity, due to $K^{40}$, was found in the glass envelope and in the ceramic bass. In fact, photomultipliers are one of the principal sources of residual radioactivity and will be discussed further later.

The 25 ppm by weight of K in the NaI crystal (*1*) contributed 4 cpm more. Subtraction of these identified activities, about 17 cpm, leave 14 cpm or 0.14 cpm/gm of NaI unexplained.

It was not considered practical to

identify the residue by its scintillation spectrum because of the extremely low counting rate; calculations showed that it would have required running times of at least 100,000 min for each suspected parameter.

## Larger-Crystal Results

A 4- × 1½-in. NaI(Tl) crystal mounted in Harshaw's standard Al and Pyrex glass case had a 7,000-cpm background between 90 kev and 2.5 Mev outside of the room. Within the iron room the background over the same energy band was 480 cpm. Further addition of either ⅛ in. of Pb or 1 in. of Hg around the crystal reduced the background to 360 cpm (0.3 cpm/gm).

The pulse-height spectrum (obtained with a Marconi 24-channel pulse-height analyzer) suggested that the bulk of these counts were due to the radium family and $K^{40}$.

Hence as in the case of the smaller crystal, it was concluded that a considerable fraction of this count must have been due to radioactivity either within the crystal, its can, or the photomultiplier assembly. (If the contaminating source were wholly exterior to the distilled-Hg shield, the addition of the latter should have attenuated it by at least a factor of four.)

Based on numerous tests, to be described in a following section on Radioactivity in Materials, the crystal was recanned in a 304-stainless-steel (s.s.) case sealed with a fused-quartz window. This effort was rewarded; the gamma-ray background dropped from 360 cpm to 150 cpm.* Pulse-height spectra, before and after recanning, are shown in Fig. 3.

The origin of the remaining 150 cpm were investigated further, by methods analogous to those mentioned before, but with the advantage of pulse-height analysis.

The contribution of a 5-in. photomultiplier was determined by placing it in front of the crystal with ¼-in.-thick piece of quartz interposed so as to approximate the true filtration existing for the tube actually used to detect the pulses. Counting rate was ~38 cpm, the absolute number varying from tube to tube.

The intrinsic K content of this crystal was determined by flame photometry to be 8 ppm, thus accounting for another 15 cpm. The pulse-height spectra of these three sources are shown in Fig. 4. Combined, they represent 93 of the 150 cpm, leaving a total of 57 cpm or 0.047 cpm/gm of NaI unidentified.

## Other Crystals

We wanted to characterize further the unidentified source of residual counts and assure ourselves that our results were not peculiar to a particular-sized crystal. Therefore, similar tests were performed on a 2½ × 2⅛-in. NaI(Tl) crystal also mounted in s.s. and quartz. The gamma-ray background of this crystal, when shielded with 1 in. of Hg, is 75 cpm in the 80–800-kev energy range.

Figure 5 shows the cosmic-ray spectrum (15 cpm), the photomultiplier spectrum (25 cpm), the $K^{40}$ spectrum (8 cpm), and the phototube noise spectrum (all below 80 kev). Those three sources account for 48 of the 75 cpm, leaving 27 cpm or 0.042 cpm per gram of NaI(Tl). The data for the last two crystals are summarized in Table 2.

Cursory checks on a 3- × 3-in. wall counter and on a 4- × 4-in. crystal have also indicated an unknown counting rate approaching 0.045 cpm/gm. Thus the residual counting rate seems proportional to the mass of the crystal. However, due to considerable statistical uncertainty in counting, appreciable difference in crystal size, and different gamma-ray scattering within the shield, we cannot state categorically whether the source of residual counts is the same in both instances. But a rough similarity does exist in the unidentified spectra in that they are confined to the region below 800 kev.

## Effects of Photomultiplier Radioactivity

It should be realized that assay of radioactivity of materials to be used as counter components within the Hg shield is always handicapped by the presence of photomultiplier activity inasmuch as the $K^{40}$ radiation scattered by the test object cannot be evaluated accurately.

Analogous effects occur when at-

* A crystal remounted in an oxygen-free high-conductivity (OFHC) copper assembly gave the same background spectra as when canned in stainless steel.

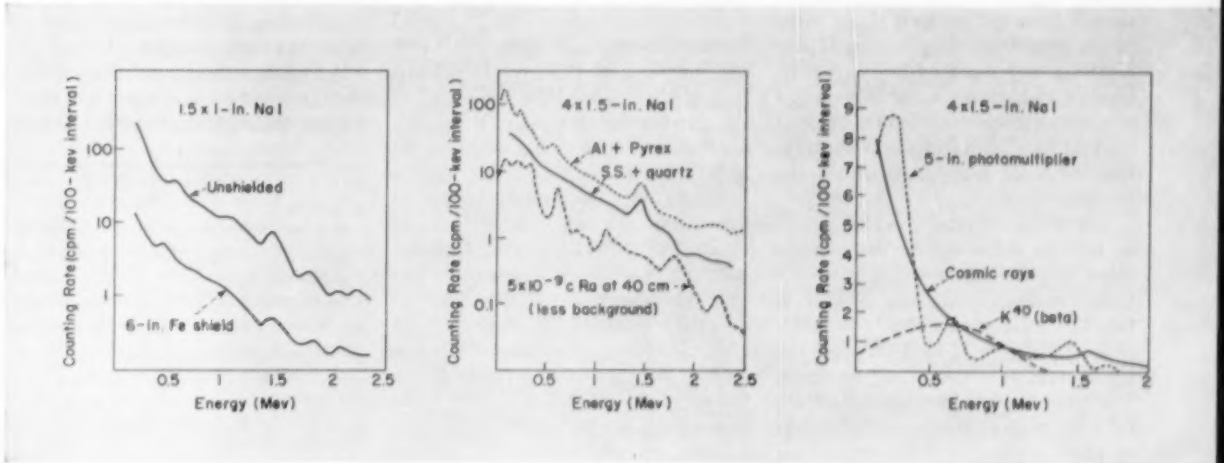


FIG. 2. Gamma-ray spectra of a 1½ × 1 in. NaI crystal with and without 6 in. of iron shielding in place on walls and top of shielding room

FIG. 3. Gamma ray background spectra of a 4 × 1½ in. NaI crystal, shielded with 8 in. Fe + 1 in. Hg, before and after remounting

FIG. 4. Gamma ray pulse height spectra of the 4 × 1½ in. NaI crystal due to 5 in. photomultiplier, cosmic rays, and the $K^{40}$ beta rays intrinsic in the crystal

tempting to obtain the spectrum from phototubes by adding another. Since the addition of the second tube alters the scattering of the first, and vice versa, the spectrum obtained by subtraction of the two runs is not strictly correct.

Similar shortcomings should be expected in low-level assay of bulk material by the same techniques.

In view of uncertainties caused by the radioactivity of the phototube, it is felt that elimination of this source hardly needs any emphasis. True, some of the counts could be eliminated by using radioactively clean light pipes, but only at the cost of complicating the apparatus. Also Cerenkov pulses in the light pipe are not eliminated entirely by coincidence techniques (this question is discussed further in the section on phototube noise).

## Sources of Residual Count

The residual spectrum of the $2\frac{1}{2}$- × $2\frac{1}{2}$-in., obtained by subtraction of the known components, is shown in Fig. 6. Its shape suggests that the residual counts might be due to fast-background-neutron activation of $I^{127}$ into $I^{126}$ (13-day half-life) by $n,2n$ reaction.

But tests with fast-neutron shielding demonstrated that this is not the case. The 4- × $1\frac{1}{2}$-in. and $2\frac{1}{2}$- × $2\frac{1}{8}$-in. crystals were placed in a $\frac{1}{4}$-in.-thick shell of Boral, a slow-neutron shield, which was in turn surrounded with 18 in. of distilled water on the sides and 3 ft of water on top. The smaller $2\frac{1}{2}$- × $2\frac{1}{8}$-in. crystal was removed from the neutron shield after 26 days and the larger 4- × $1\frac{1}{2}$-in. crystal removed after 62 days. Both crystals yielded the same background after being shielded as before, suggesting that significant fast-neutron activation does not take place within the crystals.

The smaller crystal was also placed in the Hg shield within the 8-in.-Fe room and the backgrounds were obtained as the crystal was shielded in turn by the Hg, the Hg plus $\frac{1}{4}$-in. boral, and by Hg plus $\frac{1}{4}$-in. boral plus the thickness of water described previously. There appeared to be a slight decrease (of a few percent of the residual counts at most) as the slow-neutron shield, boral, and then the fast-neutron shield, $H_2O$, were added. Thus, it would seem that neither the recoils from fast-neutron scattering, nor neutron-capture gamma rays in the crystal play a prominent role at these counting rates.

Slow-neutron activation in either I or Na is also ruled out by these experimental results, by the shape of the spectrum, and by the fact that Hg itself is a good slow-neutron absorber.

This leaves long-term neutron activation of the Hg in the shield as a possible source. But the pertinent experiment remains to be performed as are other experiments designed to determine more fully the influence of cosmic radiation and its secondaries on our apparatus.

It was suspected that the Na in the crystal might contain traces of the naturally radioactive alkali $Rb^{87}$. However, neutron-activation analyses of NaI used in crystals proved the fraction of $Rb^{87}$ to be $<10^{-8}$.

**Airborne activity.** To rule out contamination within the steel room, either airborne or otherwise, all superfluous objects were removed. The crystal was mounted in a vertical position with the sides and bottom shielded with 1 in. of Hg. A plastic weather balloon 8 × 8 × 6 ft was placed over the crystal and filled alternatively with both atmospheric air and with aged, radon-free air, thereby displacing all the other air within the room. By these means all of the radon daughters present within the room were trapped on the walls of the room and would have decayed with a 3.83-day half-life. No differences in background were obtained with the two air fillings, either immediately or over a 4-day period.

A likely possibility is that the crystal is internally contaminated with $Cs^{137}$, a fission product. The spectrum has a peak at about 0.661 Mev, the energy of the gamma ray from $Cs^{137}$, and the approximate shape expected from its betas. For all the remaining counts to be due to $Cs^{137}$, the crystal need be contaminated with only $5 \times 10^{-16}$ gm of Cs per gm of NaI. If Cs is present, however, an X-ray conversion line should be observed at 33 kev. But, to definitely establish its existence, the channel width would have to be restricted to 10 kev or less—impractically low counting rates would result. Since the residual spectrum is found by subtracting several components, each of which must be accurately known, the time for each run would be astronomical.

Thus, it is concluded that a truer spectrum of the unexplained residual counts can be obtained only when radioactivity-free photomultipliers are available.

## Radioactivity in Materials

Samples of different materials used in the vicinity of the crystals were independently checked for alpha, beta, and gamma activity using an alpha scintillation counter, a gas-flow alpha proportional counter, a gas-flow beta proportional counter, and a well scintillation counter.

A 3- × 3-in. NaI(Tl) aluminum-mounted crystal with a $\frac{7}{8}$- × 2-in. well was used for the gamma-ray measurements. Special precautions were taken during preparation of the $\frac{3}{4}$- × 2-in. test sections to assure that the pieces were not contaminated by handling. Thus, all existing surfaces were removed with clean tools and new clean tools were used for the finishing cuts. The final cut-off operation was performed so that the specimen dropped directly into a previously tested plastic bag. The work was performed in a shop as free of radioactivity as possible and no piece was touched by hand. Past experience has demonstrated that sufficient activity can be transferred to a crystal mount from supposedly clean hands to increase the crystal background by as much as 20 cpm.

All samples of Al, regardless of the supplier, assayed of the order of $3 \times 10^{-13}$ c of radium per gram of metal. This was true of samples of pure Al i.e., 2s as well as for the alloys such as 17 st, 52 st and 61 st. These results are consistent with others (*2, 3*).

According to information obtained from the manufacturer, natural K, which emits 180 gammas/min/gm, constitutes about 0.1% of the weight of the glass of the photomultipliers. The ob-

**TABLE 2—Background of Two NaI Crystals**

| *Size (in.)* | *$2\frac{1}{2}$ × $2\frac{1}{8}$ in.* | *4 × $1\frac{1}{2}$ in.* |
|---|---|---|
| *Volume ($cm^3$)* | *171* | *309* |
| *Weight (gm)* | *640* | *1160* |
| Total background (cpm) | 75 | 127 |
| cosmic | 15 | 27 |
| $K^{40}$ (beta) | 8 | 15 |
| phototube | 25 | 30 |
| left over: residual | 27 | 55 |
| specific (cpm/gm) | 0.042 | 0.047 |

served activities, as reported above, are roughly consistent with the mass of glass envelopes.

Moreover, direct observations have revealed that the material used in the bases and sockets of the phototubes contain both Ra and K and that they contribute materially to the activity of the phototube. Fortunately, no activity has been found in the internal structures of phototubes.

The gamma-ray activity of quartz, mild steel, 304 stainless steel, OFHC copper, Lucite, MgO, Dow-Corning 200 grease, NaI crystals, and Harshaw's thallium was found below the level of detection of the counter. One piece of 347 s.s. proved to be definitely contaminated. No other types of s.s. have been tested to date.

Data from the alpha and beta counters agreed with the above results in all cases, except for Lucite, inasmuch as considerable alpha activity has been found on some surfaces of Lucite.

However, very recent tests, have revealed that the cylindrical portion of the Hg shield used in all these experiments contributed about 12 cpm more than a similar structure (also of 304 s.s.) built later in our shops. These findings demonstrate the limitations of contamination tests carried out with samples of materials not used specifically in the construction of a low background apparatus, and at the same time illustrate how useful the latter can be in screening its own components.

## Photomultiplier Noise

It is common to correct for tube noise by removing the crystal and determining the resulting pulse spectrum. This procedure is incorrect for an assembly operated with its axis in the vertical direction (though horizontal is all right) since many energetic particles that normally would pass through the crystal producing large pulses would also pass through the tube and develop small pulses observed as noise. In our experience, 66% of these pulses are in coincidence with cosmic rays. But the previous practice is satisfactory if the crystal and tube are operated in a horizontal position. In any event, an anticoincidenced cosmic-ray shield over the tube will prove effective in reducing this type of background.

## Electronics

Meticulous attention must be given aspects of design and construction of low-background electronic systems that are irrelevant for conventional scintillation counters. As the gross background rate is reduced, false count rates due to defective electronics become proportionally more important and, therefore, must be eliminated.

Thus, noise pulses have been found to originate from poor contacts in the photomultiplier tube socket. The number of pulses per minute will depend upon the conditions of the spring clips in the socket and the firmness with which the tube is set in place. To eliminate this source of noise, which is usually less than 20 cpm, wires have been soldered to the pins of the phototubes, fed through holes in the socket and soldered directly to the divider string. Despite its practical inconvenience, this precaution has resulted in definite improvement in the reproducibility of the background.

A second factor, always important in pulse-height analysis, assumes special importance in this respect. It concerns the overload properties of the amplifier and the problem of reflections

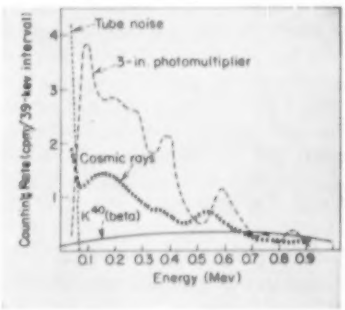


FIG. 5. Gamma ray pulse height spectra of the $2\frac{1}{2} \times 2\frac{1}{8}$ in. NaI crystal due to 5-in. photomultiplier, cosmic rays, tube noise, and the $K^{40}$ beta rays intrinsic in the crystal

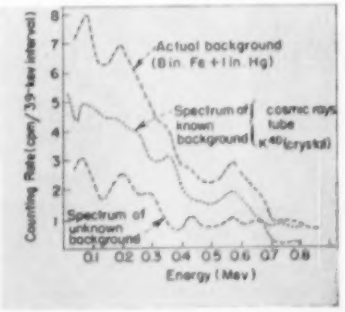


FIG. 6. Residual pulse height spectrum of $2\frac{1}{2} \times 2\frac{1}{8}$ in. NaI crystal which is obtained by subtraction of known components from the actual background

in cables. A few cosmic-ray pulses per minute will occur of magnitude equivalent to those of about 100-Mev electrons. When the sensitivity of the first channel of the analyzer is set for 10-kev pulses, this event represents a pulse 10,000 times the minimum pulse-size of interest. Consequently, reflections that are only 1/10,000th of the original pulse will appear as low energy pulses. The occurrence of these pulses, while few in number, add to the background.

A large cosmic ray pulse will overload the phototube with a resultant output pulse consisting of a flat top followed by the conventional *RC* decay. If a pulse of this shape is clipped with a delay line, a new pulse is formed which has a considerable undershoot. The negative reflection theoretically can be removed with a diode but, to be effective, the removal must be accomplished to the order of the 1/10,000 mentioned previously.

It was possible to eliminate the above difficulties in our case with the use of a modified Higinbotham-type amplifier, designed to drive all capacitance-coupled grids with negative-going pulses and to develop negative output pulses. This solution was found feasible because we use a Canadian Marconi analyzer, which requires a 0–40 volt negative going pulse input. A lengthy discussion of the amplifier is not justified here since it would not be applicable for a system using the conventional American-built analyzers, which require positive input pulses of greater magnitude.

* * *

*The authors wish to acknowledge their indebtedness to Henry F. Lucas, Jr., Andrew F. Stehney and Ralph W. Bane for the alpha analysis, the spectrometric analysis of K, and the Rb activation analysis mentioned in the text. They also wish to thank B. R. Linden of the Allen B. Du Mont Laboratories for information on the K content of the glass envelopes of their photomultiplier and E. C. Stewart of the Harshaw Chemical Company for his unstinted help in securing material samples of crystal components. Special thanks are due J. B. Macunich of the physics division of ANL for mounting the various crystals used in these experiments and to Mr. O. J. Steingraber for his technical assistance throughout the course of this work.*

*This is a condensed version, edited by the NUCLEONICS staff, of a paper presented at the fifth scintillation counter symposium. A complete version will appear in the IRE Transactions of Nuclear Science.*

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# High-Energy Cerenkov Counter

## Lead glass and 16-in. photomultiplier combine to measure the energy of Bev gamma rays

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MEASUREMENT of high-energy (>100-Mev) gamma rays has required development of large total-absorption spectrometers. Pair spectrometers, used at lower energies, are unsatisfactory because of the huge magnets required and low detection efficiency (~10% or better is required).

For a total-absorption device, the block of material must be large enough to generate and contain most of a gamma-electron shower [for a discussion of shower processes, see Kantz and Hofstadter, (*1*)]. For dense materials, this means typical dimensions $\gtrsim 1$ ft.

A second major consideration for the shower absorber is that we be able to detect the energy left in it. Practically, this requires that light be emitted and transmitted. Sodium iodide, which has been used up to the 50-Mev region, fails here because of its cost ($50,000 for the sizes required) and slow decay (which limits its usefulness near short-duty-cycle high-background pulsed accelerators). Liquid xenon (p. 37) is limited by its $10,000/liter price, though its extremely fast decay definitely would be an advantage.

Combinations of stopping material and scintillator have been investigated by Yuan (BNL); he alternated Pb glass and liquid scintillator plates (fluctuations were a problem due to the thick glass; thinner glass* now available would eliminate this difficulty). Pugh and Frisch (*2*) used a sandwich of thin lead and plastic disks with the light being viewed from the sides. A problem with this type is to make the response independent of the direction of shower development.

### The Present Counter

The Cerenkov counter described here has the virtue of being fast and discriminating naturally against low-energy background, but it suffers from low light output and fluctuations inherent in the detection process. For Bev gamma rays these problems are minimized. Resolution was better than 30% for 450-Mev electrons.

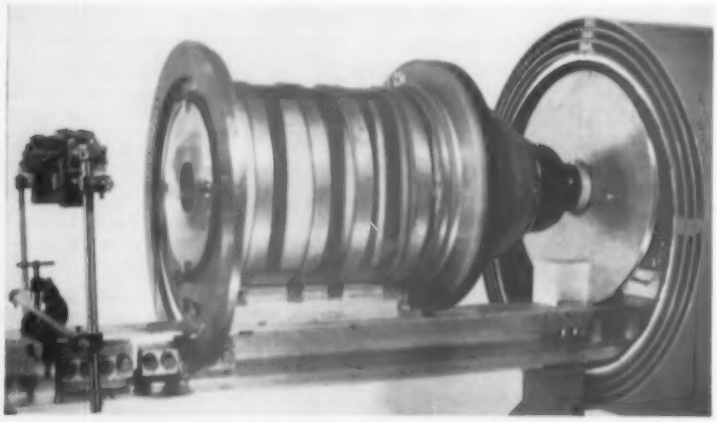
One of the obvious features of the instrument is the magnetic shielding necessary for the 16-in.-diameter tube. We have four cylinders of iron each ¼-in. thick and separated from each other by ½ in. Inside this, cushioned with foam rubber, is a cylinder of 0.025-in. mu-metal. The photocathode is normally located 18 in. in from the front of the $\gtrsim$21-in.-diameter inside cylinder.

Since there is only 450 volts between cathode and first dynode and some of the photoelectrons have to travel 9 in. before being captured, they are very sensitive to magnetic fields. One unhappy result of the long paths and nonuniform field is the slow rise time of a pulse—$5\text{–}6 \times 10^{-8}$ sec. The seal to the photomultiplier is made with a Lucite adapter ring filled with distilled water and made tight with rubber gaskets. Dow-Corning 200 silicone grease is used between the glass cylinders.

### Calibration

It is necessary to have a secondary reference so that day-to-day shifts in response can be compensated. To do this we arrange a standard light source for the shower detector. The light must come in pulses, of course, but we cannot easily duplicate showers in the lead glass to obtain Cerenkov pulses. Instead, we place a small plastic scintillator at the front end of the lead glass cylinder and illuminate this with gammas from $Co^{60}$. Such calibration runs can be made in just a few minutes; the system gain is changed easily to shift the fall-off point to its standard position. Other groups use the Cerenkov light from cosmic-ray mu-mesons going through a diameter of the glass to provide a secondary reference.

* Schott Glass Works, Germany; American representative is Fish-Shurman Corp., New Rochelle, N. Y.



**TOTAL-ABSORPTION** Cerenkov spectrometer employs 16-in. DuMont photomultiplier looking at 290-lb cylinder-pair of Corning glass 12 in. in diameter and 14 in. long

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# Better Cable for Counter Experiments

By QUENTIN A. KERNS
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*University of California, Berkeley, California*

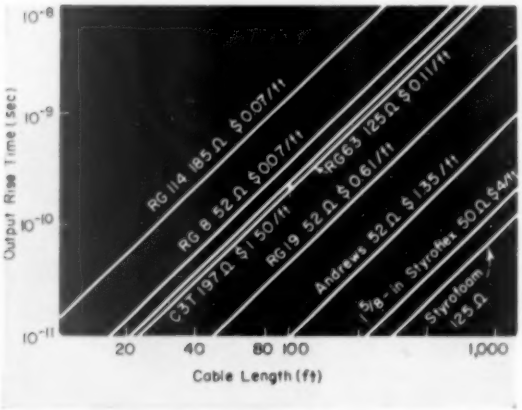



FIG. 1. Rise time to half-amplitude versus cable length for step-function input

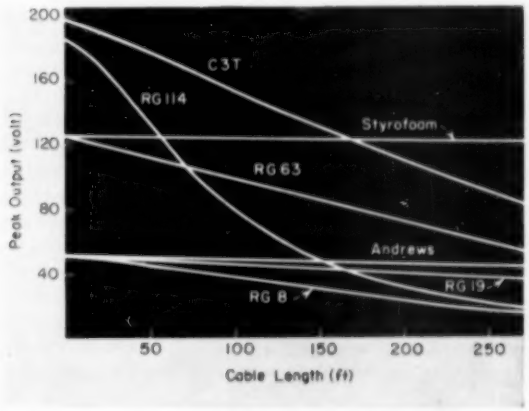



FIG. 2. Variation of peak amplitude along cable for 1-amp-amplitude 1-mμsec-duration rectangular input pulse

Coaxial cable is an important but often neglected element in counter experiments. The importance of cable increases as experiments grow in their spatial extent and as the time definition demanded of pulses goes from microseconds to millimicroseconds and below.

As part* of a program of supplying the needs of high-energy experiments, the UCRL counting research group investigated pulse distortion in coaxial cables.

**Pulse distortion.** Coaxial cables have been cataloged according to pulse characteristics. The pulse response of the cables has been measured at the output of 250-ft lengths of the various cables when energized by an input voltage step. The cathode-ray tube used was a DuMont K-1056. Time scale was about 1 mμsec/cm. The results were within ~10% of the computed values of rise time and attenuation given in Figs. 1 and 2.

Figure 1 shows output-pulse rise time to 50% amplitude as a function of cable length and type, for an input step function of voltage. This chart is computed from cable attenuation, and checks within about 10% for RG-63/U for "50%" rise times from $10^{-9}$ to $10^{-7}$ sec.

Figure 2 gives the loss in amplitude of a flat-topped voltage pulse in various cable types as a function of length. A constant charge of $10^{-9}$ coulomb is considered to have been delivered to the input terminals of the cable, the time function being a flat-topped pulse of 1 amp for 1 mμsec.

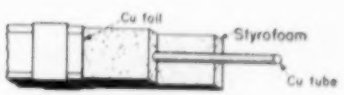
Initially, the voltage pulse will be $Z_0$ in magnitude. As the pulse is degraded in transit, it is seen that cables of low impedance (77 ohms is optimum for free space dielectric) may deliver a greater output voltage pulse at some distance than cables of greater $Z_0$ but higher attenuation.

**New 125-ohm connector.** Research and development groups at UCRL developed a constant-impedance connector for insertion in RG-63/U coaxial line. Cost is $9.50/set, and should get lower.

We use Styrofoam line for long fixed cable runs, transferring to flexible patch cables of RG-63/U at the ends where freedom of motion is essential.

## Styrofoam Transmission Line

*The semirigid Styrofoam line shown here is made as follows: a center conductor of ¼ in. copper tubing is laid out along the desired route for the transmission line. Grooved blocks of Styrofoam-22 are placed on each side of the center conductor to form a square-cross-section dielectric region 1.880 in. on a side, with the copper tubing at the geometrical center ±0.1 inches. A 1-mil-thick longitudinal run of copper foil is then folded around the Styrofoam dielectric so as to overlap about ¼ in. This copper foil outer conductor is*




*held in place by a half-lapped winding of 5-mil polyethylene film.*

*The concentric line so formed has an impedance of 125 ohms and an attenuation proportional to frequency over the range 2 Mc–4,000 Mc. The attenuation at 1,000 Mc is 0.55 db/100 ft. The cutoff frequency for the $TE_{11}$ mode is ~3,000 Mc.*

* Some of our results on photomultiplier transit time are quoted with R. V. Smith's work on p. 55.

# Towards Better Scintillation Counting

## An open discussion of why crystal resolution isn't better than it is, what phosphorescence effects there are in glass photomultiplier envelopes, and how photomultiplier gain varies with temperature

*Midway through the Scintillation Counter Symposium an open forum on current problems was held under the chairmanship of George Morton of RCA.* NUCLEONICS *presents here an account of the discussions that took place.* The reader should recognize that this was an informal discussion—some of the work is still in progress, many points are left unresolved.*

### Scintillator Resolution

There had been considerable interest aroused over why the energy resolution obtained with sodium iodide crystals is not better than it is. Work at Oak Ridge National Lab (p. 53) had shown that a considerable loss in energy resolution occurs in the scintillator itself and is not due to the statistics of the multiplier.

The discussion attempted to bring out whether others had data on this effect, whether it was observed for other scintillators, and whether anyone knew what could account for the observed effect.

First question raised was whether the fluctuations on individual pulses, (that is the "noise" on the pulse) from a crystal scintillator differed from the fluctuations on a pulse obtained from artificial scintillations of an RCA C73687 cathode-ray-tube light flasher. P. R. Bell of ORNL reported that the fluctuations on these two types of pulses were, as far as he could tell, identical. This can be interpreted to mean that the photons from a scintillator are statistically independent—this is important in that correlation of the emission of photons could account for a resolution loss.

W. Bernstein of Brookhaven had evidence that a similar loss of resolution did occur but differed with Bell's group on the energy dependence of the effect:

**Bernstein:** "I have been doing similar work; most of the results are very tentative. My analysis is based on an article by Breitenberger in the 1955 Progress in Nuclear Physics; one plots the total variance against $1/E$. If there were no intrinsic resolution loss, the curve would go through the origin. The slope of the line gives a measure of the cathode sensitivity.

Actually one gets an intercept at about 10% for anthracene. With sodium iodide you get an intercept of 4–5% with different slopes for different tubes (see Figs. 1 and 2.) The plot is linear for high energies but there is a break at about 100–150 kev. The sodium iodide crystals used for the above experiments give 7% resolution with $Cs^{137}$.

I plot against observed rather than listed energy because I find a nonlinearity in sodium iodide's energy response.

Figure 3 shows Bernstein's data.

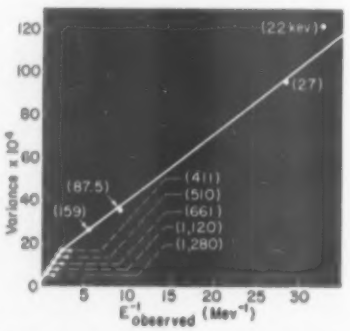



FIG. 1. Variance as a function of energy for 1½ × 1-in. NaI crystal and DuMont 6292 photomultiplier. $Cs^{137}$ resolution was 7.9%

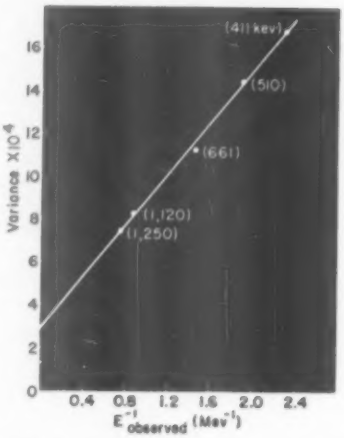



FIG. 2. High-energy section of Fig. 1 expanded to show nonzero intercept that constitutes intrinsic resolution according to Bernstein

Nonlinearity in sodium iodide response is important to the question of scintillator resolution because it could be a source of the observed intrinsic resolution.

Bernstein amplified his comments on the lack of proportionality between the light output from a sodium iodide crystal and the energy of the incident particle and Bell responded in the following exchange:

**Bernstein:** "On this nonlinearity in sodium iodide, we tried to check the linearity of a 100-channel analyzer with various sources. The approach failed because the crystal output pulse height was itself not linear with energy. Pulse response falls off with energy giving a 25-kev intercept for the upper straight-line portion."

**P. R. Bell:** "We find the energy response of sodium iodide strictly linear, though side effects can make it otherwise."

**Bernstein:** "We used five crystals and five tubes; crystals varying from a cleaved chip used for particles with

* This account has been prepared jointly by D. I. Cooper of NUCLEONICS, who took the original notes, and G. A. Morton of RCA, who provided the commentary that brings the entire account together. Speakers have had an opportunity to correct their quoted remarks, but final responsibility for accuracy rests with the editors of NUCLEONICS.

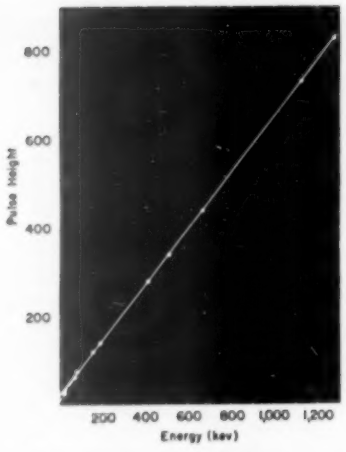



FIG. 3. Bernstein's NaI response curve. Above 200 kev curve is linear and extrapolates to −25-kev intercept. Below 200 kev points bend toward origin. ORNL group observes strict linearity

energy of 200 kev and down on up to large crystals, and definitely find the nonlinearity."

At this point the question of the linearity of response was set aside. It seems more experimental data are needed even in this fundamental question.

Returning to the question of why scintillator resolution was not better, R. K. Swank (Argonne) offered a possible mechanism. He pointed out that the light output varies with the activator concentration in a crystal; thus he felt that possibly some of the loss of resolution could be the result of the statistical fluctuations in the thallium concentration in a crystal. To this Kelley replied, "We got the same results when we progressively cut down the size of the scintillator crystal. I'd be surprised to find that the thallium concentration has such a fine structure."

However, further discussion showed that this did not meet Swank's point since he referred to the random statistical fluctuation one would expect in view of the relatively small number of thallium atoms.

Thus the source of crystal resolution difficulties remains unknown, but the effect is very clearly established.

## Phosphorescence in Glass

R. L. Madey of Brookhaven raised the next main question—why dark noise increased after a multiplier had been exposed to a bright light.

Morton pointed out that the work of Baumgarten in Zurich on the after emission of cesium antimony might have a bearing on this. Engstrom (RCA Lancaster) stated, "We observe a similar effect and have studied it as a function of the exciting wavelength. The decay is hyperbolic."

Bernstein then asked whether some of this effect could not be attributed to phosphorescence in the glass.

This question was not resolved inasmuch as a good many people had apparently observed phosphorescence in glass while, on the other hand, in experiments where one multiplier is exposed to light and then brought into darkness (the condition under which the dark current is observed), and a second multiplier that has been kept in darkness is put in optical contact with it, no increase in dark current is observed in the second multiplier. If the effect were due to phosphorescence of the glass, one would expect the second multiplier to observe the light from the first.

Further evidence for glass phosphorescence came in this exchange:

**Bernstein:** "The situation is really a common one. People observe the fluorescence in vials used in liquid scintillation counting."

**S. Friedland (NDA):** "At the Radar Research Laboratory in Malvern, England, where they have the problem of bringing a light source down from 5 to 8 orders of magnitude in 10 μsec, they find a tail in the light pulse due in large measure to glass phosphorescence."

Next point was whether there is phosphorescence or afterglow in scintillation crystals, particularly in sodium iodide. John Harshaw (Harshaw Chemical Co.) was questioned on this and indicated that there might be such an afterglow but was not prepared to give a quantitative estimate. He said, "It is one of the variables not yet eliminated from our crystals. We know that it is present and that it may vary by an order of magnitude from one crystal to another."

Zar of National Radiac contributed, "This factor which gives you light would be increased for crystals with color centers. These are F centers, produced by accidental oxidation during growth. They are not desirable characteristics. Color centers turn pink upon exposure to strong light, then bleach out by heating the crystals in the dark. These crystals have poor resolution. I don't know to what extent. Since we don't know the extent to which there may be slight color centers in normal crystals, it seems a good idea to keep crystals in the dark."

## Multiplier Temperature Effects

There seem to be as many versions of the temperature dependence of photomultiplier gain as there are observers. At the evening forum one group reported decreasing gain with increasing temperature; Bell reported essentially constant gain in at least one case. Earlier that day (p. 49) Seliger of NBS had reported increasing gain with increasing temperature. Actually temperature effects can be complicated by factors elucidated in the following:

**F. Kinard:** "At DuPont Savannah River we have found decreasing gain with increasing temperature with 5819's, 6292's and 6655's. The crystal temperature is kept constant while the

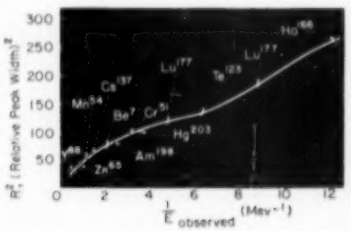



FIG. 4. Resolution squared versus inverse energy as observed by ORNL group. Quantity plotted is linearly related to Bernstein's variance, so absence of straight-line relation contradicts his result

temperature of the tube is being raised from −20° to +50° C. The change in gain is 20–40% for this 70° rise. It is a nonlinear function of temperature."

**Bell:** "We had some 5819's but they were steady with temperature. Generally we find multiplier temperature effects are small."

Morton raised the question as to whether the tube and its interior structure were in thermal equilibrium because if this was not the case, there would be a redistribution of cesium which could change gain either way.

Kinard then stated, "It takes an hour and a half for the photomultiplier to come to temperature equilibrium."

It was brought out by Martin (McCullough Tool) that great care must be taken in changing the temperature of a multiplier to be certain that no change occurs in the bleeder or socket due to a change in moisture.

Scintillators

Gamma-Ray Fluorescence of Solutions Containing Various Metal Salts

| Salt | Salt concentration* (gm/l) | Relative* intensity (%) | Effects of naphthalene: Conc. (gm/l) | Effects of naphthalene: Rel.* intensity (%) | Effects of naphthalene: Conc. (gm/l) | Effects of naphthalene: Rel* intensity (%) |
|---|---|---|---|---|---|---|
| Lithium chloride | 10 | 35 | 5 | 55 | 20 | 85 |
| Sodium chloride | 15 | 40 | 5 | 60 | 15 | 75 |
| Sodium bromide | 15 | 30 | 5 | 45 | 40 | 100 |
| Sodium iodide (5% $H_2O$) | 6 | 25 | 5 | 35 | 25 | 50 |
| Sodium iodide (10% $H_2O$) | 20 | 4 | 10 | 10 | 70 | 15† |
| Potassium bromide | 15 | 30 | 5 | 45 | 50 | 100† |
| Potassium iodide | 10 | 8 | 5 | 10 | 70 | 30 |
| Potassium nitrate | 15 | 35 | 5 | 55 | 50 | 125 |
| Cupric nitrate | 15 | 25 | 5 | 35 | 50 | 70 |
| Silver nitrate | 10 | 15 | 5 | 20 | 60 | 50 |
| Lead acetate | 15 | 55 | 5 | 85 | 70 | 150 |
| Uranium nitrate | 15 | 15 | 5 | 20 | 70 | 40 |

* Solvent is *p*-dioxane + water 20%; fluorescing solute is 2,5-diphenyloxazole (~5 gm/l). Intensities are measured relative to this as standard, without salt or naphthalene.
† Two phases at room temperature.

# Liquid Scintillators with Heavy Elements

By HARTMUT P. KALLMANN, MILTON FURST, and FELIX H. BROWN
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NAPTHALENE, BIPHENYL, and other compounds serving as intermediate energy transferrers make possible efficient liquid scintillation solutions that contain compounds, including those of heavy elements, that would otherwise diminish the fluorescent light output tremendously (*1–3*).

This can broaden the area of application of liquid scintillation counting techniques in which radioactive materials are put directly into the solution, thus avoiding losses due to geometrical factors. The method is not limited to inorganic materials but also can be applied to organic materials of special interest in biological work. In some concentration one can hope to get anything into a liquid scintillation system.

To reach this goal two basic difficulties had to be overcome:

**1. Insolubility.** Solvents in which good high-energy-induced fluorescence (HEIF) occurs are often not suitable solvents for many desired compounds.

**2. Quenching.** Many of these compounds, particularly those of heavy elements, quench the fluorescence. This is due mainly to a quenching of the excited solvent molecule; this in turn results in a reduced energy transfer to the fluorescent solute. Quenching of the excited solute molecules occurs as well, but to a smaller degree.

The use of an "intermediate solvent," by which is meant an intermediate energy transferrer, makes other solvents available. Naphthalene and biphenyl are among the best intermediate energy transferrers we have found up to now, but other molecules can be used. They also overcome the quenching effect considerably. In this way solutions can be produced that contain at least a small amount of a compound of a heavy element or of another interesting chemical compound, and that, despite the quenching effects of these molecules, display a fluorescence comparable to that of a usual xylene solution.

The table presents a survey of experiments with salts of elements scattered through the periodic table. The enhancement of light output when various amounts of naphthalene were added is shown. Solubilities of the salt and of naphthalene are limited because both act to produce two phases; thus, with a given salt concentration the content of naphthalene could not be made as large as desired. The table clearly shows that many inorganic salts can be used and considerable fluorescence retained. With smaller amounts of inorganic salts, the fluorescence can be increased because of two effects: the quenching of the salt becomes less and more naphthalene can be added.

For these high-energy measurements the arrangement is essentially the same as previously reported (*1*).

*A complete account will be published in the IRE Transactions on Nuclear Science.*

* Work supported by Signal Corps Engineering Laboratories, Evans Signal Laboratory, Belmar, N. J.

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# Liquid-Scintillator Temperature Effects

By H. H. SELIGER and C. A. ZIEGLER
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*Washington, D. C.*

DuMont 6292 and RCA 5819 photomultipliers exhibit a slight decrease in response with decreasing temperature. The light outputs of three gas-free liquid scintillators (DPO, αNPO, and PBD, each dissolved in xylene) increase markedly with decreasing temperature. It may be possible to obtain a liquid scintillator more efficient than anthracene. These are the results of measurements described here.

## Photomultiplier Response

A light-pulse generator like that of Kinard and Struthert (*1*) was used to excite the photomultipliers inside a light-tight refrigerator from the outside via a light-tight Lucite light-piper. Sharp-cut-off optical filters were used to select ~100-Å bands at 4,900 and 5,900 Å; the peak and long-wavelength end of the standard S-9 response curve.

The intensity of the light source was adjusted so that the output pulse height was about that from a NaI(Tl) crystal mounted on the face of the phototube and excited by $Ba^{137}$ gamma-rays. The pulse-height spectrum was obtained with a single-channel pulse-height analyzer. The position of the peak was used as an index of the response of the phototube (see Fig. 1).* Photomultiplier response was the same whether or not dynode bleeder was inside the refrigerator.

## Liquid Scintillator Response

Because of the well-known quenching effect of dissolved oxygen (*2–5*) measurements were carried out with gas-free scintillating solutions. In addition, since the quenching by oxygen is dependent upon solute concentration, temperature effects were measured at concentrations close to optimum at room temperature (*6*).

Particular care was taken in the preparation of solutions to insure that they were gas-free and pure. Weighed samples of solute were placed in 5-ml Pyrex absorption cells tubulated onto a vacuum system. The solvent, 99.5%-pure *m*-xylene, was poured into another vessel on the system and alternately frozen with liquid $N_2$ and thawed under high vacuum ($10^{-4}$ mm) three times to remove all traces of dissolved gases. Appropriate volumes then were distilled into the individual cells, which then were flame-sealed off.

The cells were laid on the photomultiplier face and surrounded by an aluminum reflector. A copper-Constantan thermocouple, in direct contact with the glass cell, was used to determine solution temperatures.

Position of the peak of the pulse-height distribution from a Po alpha source sealed within the cell is plotted vs. temperature in Fig. 2.

Measurements were also performed for gas-free solutions of 2.5 gm/l DPO in *m*-xylene and 1 gm/l anthracene in *m*-xylene. The slopes in these cases were approximately 0.6%/° C and 1%/° C, respectively. Pulse heights in the anthracene solution were ⅓ the DPO pulses.

Preliminary measurements (*8*) made with DPO in xylene from 28° to 0° C using gamma-ray excitation agree with the present alpha-particle data. One might have assumed that there would be self-quenching of the alpha-particle excitation due to the high density of excited solvent and solute molecules near the dense alpha-particle track, and that the increases in light output noted were due to reduced self-quenching of the solvent. The gamma-ray results seem to contradict this—the effect is as striking for their secondary beta particles whose specific ionization is much lower.

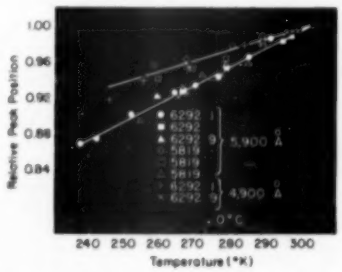


**FIG. 1. Phototube response curves. The three 5819's decrease 0.13%/° C; two 6292's decrease 0.2%/° C; the third 6292, intermediate between these, was used for the liquid-scintillator temperature-response measurements**

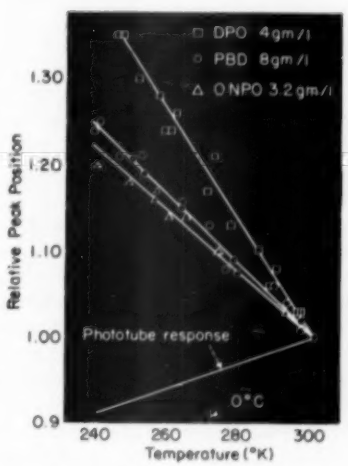


**FIG. 2. Relative output pulse heights from liquid scintillators as a function of temperature. Slopes of DPO and PBD curves are 0.6%/° C and 0.4%/° C, respectively. To determine actual scintillator temperature response, upper curves should be multiplied, at each temperature, by reciprocal of relative photomultiplier response given at bottom**

* G. A. Morton informs us that recent measurements at RCA show a shift toward shorter wavelengths of the 1%-response point for Cs-Sb photo-cathodes. This shift amounts to −2Å/° C. The fact that the same temperature effect was observed for both light sources is evidence that the shift he reports is important only at the foot of the response curve.

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# Spectrum and Decay of NaI

By WESLEY VAN SCIVER
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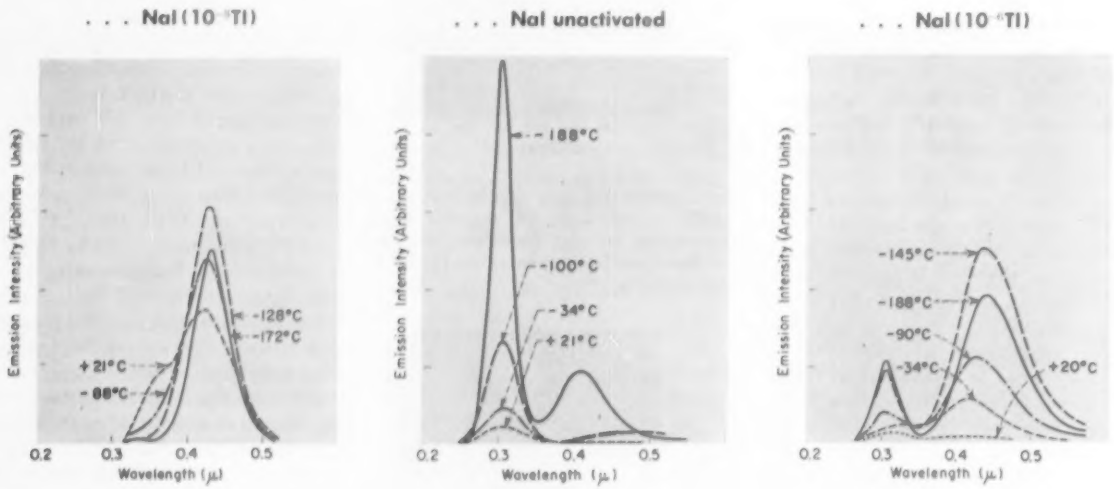
THE SPECTRA of the luminescence from unactivated NaI and thallium-activated NaI were measured in the temperature range −190° C to +20° C using alpha particles, gamma rays, and ultraviolet light as sources of excitation. The characteristic emission from NaI ("pure") is in a band centered at approximately 0.3μ. The intensity is weak at room temperature but increases by a factor of ten in cooling the crystal to −190° C. By comparison, the characteristic emission from the commonly used NaI($10^{-3}$Tl) is in a band centered at approximately 0.42 μ and changes in intensity by a factor of less than two over the above temperature range. The intensities are nearly equal at −190° C. Another crystal, NaI($10^{-6}$Tl), was weakly luminescent at room temperature, but emitted both bands strongly at the lowest temperature with a total intensity nearly equal to the intensity for NaI($10^{-3}$Tl). Figs. 1–3 show the results.

The characteristic decay time of the scintillation light from unactivated NaI was found to vary between $10^{-8}$ sec at 20° C and $3 \times 10^{-8}$ sec at −190° C (Fig. 4). The pulse height divided by particle energy at −190° C is nearly equal to that of NaI($10^{-3}$Tl) at 20° C. The high luminescent efficiency, rapid decay time, and relatively high density of unactivated NaI at −190° C make it a unique scintillation material that may prove to be useful in experiments.

The desired degree of understanding of the NaI scintillation phenomenon has yet to be achieved. A qualitative understanding that seems to be internally consistent is that:

1. In being stopped or slowed down in a crystal, a high-energy ionizing

## Emission curves from $Co^{60}$-excited crystals of . . .




**NaI(Tl).** *The Tl-activated crystal exhibits room-temperature emission curves of the same shape when excited by gamma rays or alpha particles (left). With decreasing temperature, the peak of the alpha-particle-produced spectrum rises monotonically while the maximum of the spectrum shifts monotonically toward longer wavelengths. On the other hand, the gamma-produced spectrum rises to a maximum in the vicinity of −130° C and then decreases with decreasing temperature. The maximum of the gamma-excited emission curve shifts monotonically toward longer wavelengths. A small component is apparent in the region of 0.34 μ. Its magnitude appears roughly temperature independent, while the location of its maximum shifts toward shorter wavelengths with decreasing temperature.*

**"Pure" NaI.** *This crystal exhibits a strongly temperature-dependent peak in the vicinity of 0.31 μ at room temperature. The peak shifts to 0.303 μ at −190° C (center). A distinction between the alpha- and gamma-produced families of curves appears in the long wavelengths. In particular, there is considerable emission at approximately 0.41 μ. This peak is much smaller with alpha-excitation.*

**NaI($10^{-6}$Tl).** *With a trace of Tl ($\gtrsim 10^{-6}$ mol fraction), the spectrum of the figure on right shows an attenuation of the gamma-excited 0.3-μ band to ~ 10% of the intensity in the pure crystal. A trace of Tl also attenuates the alpha-particle-excited 0.3-μ band. But the attenuation is only 2:1 instead of 10:1 as indicated for gamma excitation. A considerable emission occurs in the 0.43-μ band, but its intensity exhibits greater temperature dependence than does the heavily activated crystal. Also exhibited is a rise to a maximum at an intermediate temperature and a drop to lesser efficiency at −188° C. Ordinates are represented in arbitrary units; scale of figure at right is expanded by factor of 2 relative to other figures. Comparisons of ordinates is approximate—they are normalized for source energy and flux.*

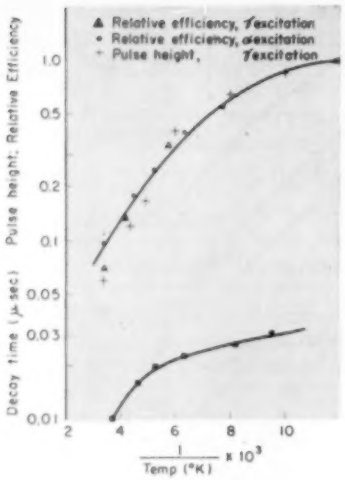



FIG. 4. Decay times, relative pulse heights, and relative luminous efficiency of the 0.3-$\mu$ band in pure NaI scintillations as functions of temperature. At −188° C, the 0.41 $\mu$ band decays very slowly in a complex way not resolvable into a single exponential. Longest characteristic time investigated is of the order of hours. The 0.3 $\mu$ band exhibits a rapid decay comparable to that of anthracene. That the temperature dependence of the relative efficiency and decay time are not proportional suggests existence of a capturing agent in the crystal the existence of which is temperature dependent

particle gives up its kinetic energy to the crystal matrix. This results in the creation of excitons,* electrons in the conduction band, and holes in the filled band.

**2.** In a perfect crystal, the electrons and holes would wander about until they all had paired up to form excitons. The exciton energy may be radiated by some as-yet-unknown center conceivably "created" by the polarization capture of the exciton in the perfect crystal lattice.

**3.** Since all real crystals will contain imperfections that can capture electrons, holes, or both, the degree of pairing up of electrons and holes to form excitons will depend on the relative probability of encounter by the electron of a hole or an imperfection capable of capturing it. Thus, the pairing up will depend on the density of ionization produced by the initial high-energy particle. Thus, for example, F-centers or a trace of thallium impurity in NaI will be more effective in preventing the formation of excitons from the pairing up of electrons and holes when the primary excitation is by gamma rays (which produce high-energy electrons in the crystal) than when it is by alpha particles.

**4.** A moderate concentration of Tl ($10^{-2}$ mol fraction) results in the capture of virtually all electrons and holes and in the capture of excitons as well. This places the Tl centers in excited states essentially identical with those reached by direct excitation through the absorption of ultraviolet.

**5.** The successive capture of electrons and holes makes it possible for the Tl center to be placed in metastable states not normally accessible by capture of an exciton or a photon. This leads to trapping at low temperatures and, consequently, to considerably more thermoluminescence by gamma-ray excitation than by alpha-particle or ultraviolet excitation.

* * *

*Research, performed at W. W. Hansen Laboratories, Stanford U., and Levinthal Electronic Products, Inc., was supported in part by ONR and USAEC.*

* The exciton is most readily thought of as an electron and a hole bound together by electrostatic force in a hydrogen-like atomic state.

# How Much Do Cerenkov Counters Scintillate?

By RICHARD MADEY and LAWRENCE LEIPUNER
*Brookhaven National Laboratory, Upton, New York*

IN USING Cerenkov counters, one must be sure that the scintillation light output is significantly less than the Cerenkov light.

The 40-Mev alpha particles in the external beam of the Brookhaven 60-in. cyclotron are slow enough not to give Cerenkov light,* neither will their "knock-on" electrons. Therefore, the ratio of the d-c output from an RCA-6342 photomultiplier to the alpha-particle beam current was taken as a (relative) measure of scintillation output.

Beam current was monitored by counting alpha particles elastically scattered from a foil. After passing through the foil, the beam passed out the evacuated scattering chamber, through a 1-mil Al window, then through 6 in. of air, and finally into the test substance through a 3-mil brass window. At this point the beam energy was 35 Mev.

The relative light outputs from some transparent media excited by 35-Mev alpha particles is given in the table. Background gave a negligible contribution to the relative light output. It was measured by stopping the alpha beam in $\frac{1}{16}$ in. of aluminum inserted ahead of the substance studied.

* A charged particle will not radiate Cerenkov light if it is moving more slowly than a critical velocity given by the reciprocal of the refractive index of the medium.

**Relative Scintillation Light Output of Cerenkov Media**

| *Substance* | *Index of refraction (NaD line)* | *Rel. light output (per alpha)* | *Rel. light output (per Mev loss)* |
|---|---|---|---|
| Distilled $H_2O$* | 1.33 | 1.00 | 1.00 |
| Tap $H_2O$ | 1.33 | 0.90 | — |
| Sugar $H_2O$ (50 wt % sucrose) | 1.42 | 1.3 | — |
| $CS_2$ | 1.64 | 1.7 | — |
| Toluene | 1.498 | 65 | — |
| Toluene +2% benzaldehyde | 1.499 | 3.2 | — |
| Toluene +4% benzaldehyde | 1.50 | 3.7 | — |
| Plexiglas‡ | 1.49 | 170 | — |
| Lead glass§ | 1.8 | ~15‖ | — |
| Pilot B¶ | | ~3 × 10⁵** | ~3 × 10⁵ |
| Air | 1.0003 | | ~1 × 10³ |

* Sterile, nonpyrogenic, distilled water.
‡ Ultraviolet-absorbing variety.
§ Penberthy Instrument Co., Seattle, 8, Wash. (composition: 65% PbO and 35% $P_2O_5$).
¶ Pilot Chemicals, Inc., Waltham, Mass.
‖ Lead-glass result includes a 20–30% subtraction for air scintillation.
** Least accurate result here—monitor was not sensitive at low beam currents required.

# Peak Efficiency of NaI

By N. H. LAZAR, R. C. DAVIS, and P. R. BELL
*Oak Ridge National Laboratory*
*Oak Ridge, Tennessee*

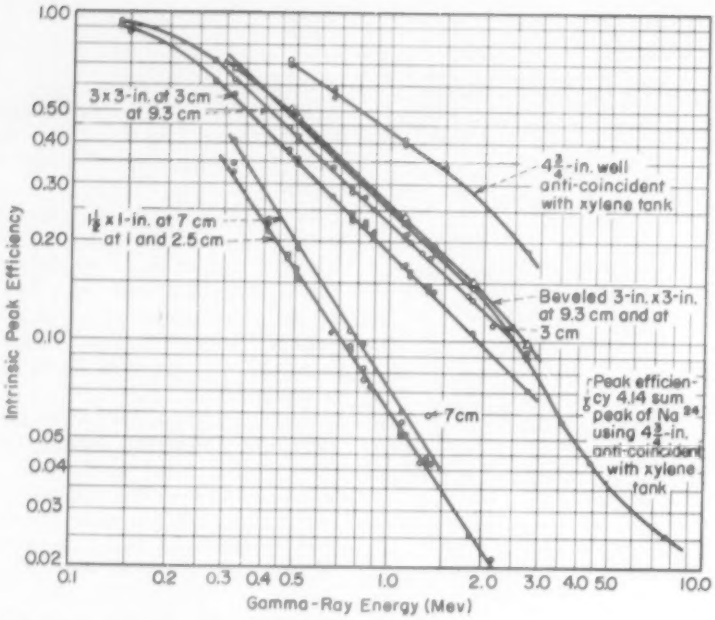

Intrinsic Peak Efficiency
Gamma-Ray Energy (Mev)
3x3-in. at 3cm at 9.3 cm
1½ x 1-in. at 7 cm at 1 and 2.5 cm
4¾-in. well anti-coincident with xylene tank
Beveled 3-in. x 3-in. at 9.3 cm and at 3 cm
Peak efficiency 4.14 sum peak of Na24 using 4¾-in. anti-coincident with xylene tank
7cm

FIG. 2. Peak efficiency vs energy for NaI crystals

SCINTILLATION COUNTERS are ideally suited for the measurement of absolute gamma-ray intensities since they have a well-defined sensitive volume. The problem is to relate the counting rate observed to the intensity of gamma rays. The shapes of the full-energy peaks are not greatly affected by scattering or by other gamma radiation as is the lower-energy Compton distribution. It is therefore practical to relate the intensity of the incident radiation to the area under these peaks.

This approach to the measurement of gamma-ray intensities is very powerful since the efficiencies as defined are independent of variations in resolution and surrounding scatterers. Thus, curves of efficiency should prove useful for many applications.

We define the peak efficiency, $\epsilon_p(E)$, of a scintillation spectrometer as the probability that a gamma ray of energy $E$ will cause a pulse that will fall in the full-energy peak if it strikes the crystal. Thus, the intensity of gamma radiation of energy $E$ is related to the area under the full-energy peak by the peak efficiency and solid angle. We have developed a method of determining $\epsilon_p$ over the range 0.150–2.76 Mev for 1½- × 1-in. and 3- × 3-in. NaI(Tl) cylinders and a 3- × 3-in. cylinder with ½ in. bevelled off the radius and height.

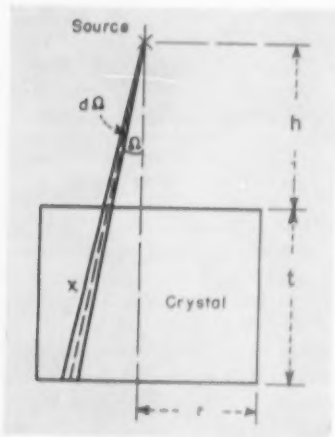



FIG. 1. To calculate $\epsilon_i$, consider geometry above. If $I_0$ is total intensity of $\gamma$-rays leaving the source, $I_0 d\Omega$ will be number of $\gamma$-rays striking crystal in solid angle $d\Omega$; $I_0 d\Omega(1 - e^{-\tau x})$ will be the number detected by crystal ($\tau$ is total absorption coefficient for NaI and $x$ is path length in crystal, a function of $\Omega$). Thus, $\epsilon_i \Omega = \int_{stal}(1 - e^{-\tau x})\, d\Omega$ where integral extends over crystal face

Because of the high probability for multiple collisions in the crystal, it is difficult to calculate $\epsilon_p$ directly. However, it is a relatively simple matter to calculate $\epsilon_i(E)$, the total efficiency of the crystal for a gamma ray of energy $E$ (see Fig. 1).*

Our approach has been to determine $\epsilon_p$ by a measurement of $R$, the ratio of the area under the full-energy peak to the area under the total spectrum, for several sources that emit only one or two gamma rays; then $\epsilon_p = R\epsilon_i$.

We measured $R$ at two distances from each of the crystals. Single gamma rays could be used from 0.145 Mev ($Ce^{141}$) to 1.114 Mev ($Zn^{65}$), but at 1.85 and 2.76 Mev only sources that emitted two gamma rays were available. The contribution to the total area from the lower-energy gamma rays in $Y^{88}$ and $Na^{24}$ were determined by fitting a Gaussian shape to the full-energy peaks observed for these radiations and using the value of $R$ that already had been determined for that energy. Above 2.76 Mev, gamma rays from $(p,p')$, $(p,\gamma)$ and $(p,\alpha)$ reactions were observed with the 3- × 3-in. cylinder at 3.57, 4.43 and 7.48 Mev. The peak-to-total ratio was obtained from other similar reactions at 2.14 and 1.78 Mev and agreed excellently with the curve determined from sources.

The curves of $\epsilon_p$ vs. $E$ are shown in Fig. 2. Note that points fit curves for the 3- × 3-in. crystals within 5% to 2.76 Mev. Agreement is almost as good for the smaller crystal.

To reduce scattering, crystals were suspended in an empty room in which the nearest walls were ≥4 ft away. Bremsstrahlung was reduced by suitable choice of sources and the introduction of a minimum amount of polystyrene absorbers to stop the beta rays.

These values of efficiency have been checked at several energies by a $\beta$-$\gamma$ coincidence experiment using sources in which it is known that essentially all beta rays are in coincidence with gamma rays. The values agreed with the curve obtained by the method described above, in every case, to better than 3%.

In addition, the intensities of several gamma rays have been compared to the disintegration rates measured for certain isotopes by $4\pi$ $\beta$-counting techniques and the agreement was always within 5%.

* This has been done for all of our crystals. Wolicki of the Naval Research Laboratory has extended these calculations to include all standard cylindrical crystals.

# Intrinsic Scintillator Resolution

By G. G. KELLEY, P. R. BELL, R. C. DAVIS, and N. H. LAZAR
*Oak Ridge National Laboratory, Oak Ridge, Tennessee*

CONSIDERABLE DISPARITY exists between the best obtainable crystal resolution and the resolution at equal output pulse heights from an artificial light flash. There seems to be a source of line width that is intrinsic to the scintillation crystal.

**Evidence.** We compared flasher line width vs. NaI line width for a number of photomultipliers. Resolution was measured by the fractional width of the line at half-counting-rate for 661-kev $Cs^{137}$ gamma rays and for the flasher adjusted to give equal pulses. The crystal represented about the best resolution obtainable—6.8% width for the $Cs^{137}$ line.

The square of the crystal line width varies directly with flasher-line-width squared except for an additive constant. On the assumption that flasher line width represents tube resolution, the intercept of the line through the data with zero flasher line width represents intrinsic crystal resolution. On this basis the intrinsic resolution of this crystal is 6.2% at 661 kev.

The attenuation of the light from the crystal with a given photomultiplier also produces a relationship consistent with the idea of an intrinsic resolution. Table 1 records such an experiment. A light piper with aluminum foil, bare, and wrapped with black Scotch tape attenuates the light. The square root of the difference of the square of crystal and the pulse resolution, is the intrinsic resolution of the crystal. It seems to be about 6.1%

Francis McGowan measured resolution as a function of gamma-ray energy using a 3 × 3 NaI crystal on a 6363 tube. An analysis from the point of view of intrinsic resolution is shown in Table 2. Measured line width is $R_{tot}$; $R_{xtal}$ is the calculated crystal line width on the basis of an assumed pulser line width $R_{tube}$ of 4% at 661 kev. The intrinsic line width is very nearly proportional to $E^{\frac{1}{2}}$. (See p. 46.)

**Mechanism.** To determine whether resolution varied with the angle of entrance of the light, we checked a tube that gave 4.4% flasher resolution with semicollimated light. Using a polyethylene diffuser optically coupled to the tube, the resolution was unchanged.

To rule out the possibility of instrumental difficulty, crystal and light flasher were used simultaneously. The results were the same.

We ruled out gross crystal nonuniformity as a possibility by reducing a crystal in size in three steps starting with a piece that measured about $1\frac{1}{4} \times \frac{3}{4} \times \frac{1}{2}$ in. Line width was 7.4%. This piece was reduced to about $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{4}$. Its line width measured 7.3%. This piece was further reduced to about $\frac{1}{8} \times \frac{1}{8} \times \frac{1}{16}$ with no change in the resolution.

Finally, the smallest piece was broken and a fragment about half the size of the head of a safety match was ground flat on one side and measured. The low-energy side of the peak was filled in considerably by electron escape but a gaussian fitted to the high-energy side measured 7.4%.

This experiment seemed also to rule out the possibility that the intrinsic crystal resolution was due to a slight nonlinearity in response with electron energy. With the smallest crystal, the possibility of a multiple process giving rise to a pulse in the peak is very slight.

This experiment and others using larger crystals and collimated sources indicate that difference in light collection from different parts of the crystal is not responsible for the smearing.

We have tentatively concluded, having ruled out every other possibility that we have thought of, that the smearing is produced in some manner by the details of individual interactions. We will pursue the subject further. We intend to learn whether this effect is basic and unremovable.

**TABLE 1—Piper Attenuation Experiment**

| *Condition* | *Pulse height* | *Crystal resolution* $A$ | *Pulser resolution* $B$ | $\sqrt{A^2 - B^2}$ |
|---|---|---|---|---|
| Piper + black tape | 650 | 8.65 | 5.9 | 6.4 |
| Piper alone | 950 | 8.0 | 4.9 | 6.4 |
| Piper + Al foil | 1,150 | 7.4 | 4.4 | 6.0 |
| No piper | 1,400 | 7.3 | 4.0 | 6.1 |

**TABLE 2—Crystal Resolution as a Function of Energy**

| *Source* | $E_\gamma$ *(kev)* | $R_{tot}$ | $R_{xtal}$ | $R_{tube}$ | $R^2_{xtal}$ | $R^2_{xtal}E^{\frac{1}{2}}$ |
|---|---|---|---|---|---|---|
| $Ho^{166}$ | 81 | 16.19 | 11.5 | 11.4 | 132 | 119 |
| $Lu^{177}$ | 113 | 13.5 | 9.41 | 9.67 | 88.5 | 94.1 |
| $Te^{133}$ | 159 | 11.5 | 8.1 | 8.16 | 65.43 | 82.5 |
| $Lu^{177}$ | 208 | 10.9 | 8.27 | 7.13 | 68.4 | 98.6 |
| $Hg^{203}$ | 279 | 10.14 | 8.06 | 6.15 | 65 | 109 |
| $Cr^{51}$ | 320 | 9.89 | 8.1 | 5.75 | 64.8 | 116 |
| $Au^{198}$ | 411 | 9.21 | 7.69 | 5.07 | 59.1 | 120 |
| $Be^{7}$ | 478 | 8.62 | 7.22 | 4.70 | 52.2 | 114 |
| $Cs^{137}$ | 661 | 7.7 | 6.6 | 4.0* | 43.6 | 112 |
| $Mn^{54}$ | 835 | 7.26 | 6.33 | 3.56 | 40.0 | 116 |
| $Bi^{207}$ | 1,067 | 6.56 | 5.75 | 3.15 | 33.1 | 108 |
| $Zn^{65}$ | 1,114 | 6.29 | 5.48 | 3.08 | 30.1 | 100 |
| $Na^{22}$ | 1,277 | 6.07 | 5.35 | 2.87 | 28.6 | 102 |
| $Y^{88}$ | 1,850 | 5.45 | 4.9 | 2.39 | 24 | 103 |

* Assumed.

# What's New in Photomultipliers? . . .

## . . . Bigger Photomultipliers, More Rugged Ones, Too

*By Bernard R. Linden, Allen B. Du Mont Laboratories, Inc., Passaic, N. J.* Since the last scintillation counter symposium (NU, March '54) important progress has been made with large-area photomultipliers. A 16-in. tube has been in production for several months while 12- and 21-in. tubes are just now emerging from the developmental stage. Since these tubes mostly will be used with plastic or liquid phosphors, twelve dynodes have been used for greater amplification. These tubes all use silver-magnesium dynodes.

Structures of standard production-type photomultipliers have been made more rugged. Figure 1 shows an early multiplier structure mount alongside one of the more recent ones from a Du Mont type-6292 multiplier phototube. Note heavier support springs and improved method of holding the dynodes in place. The tabs are now part of the dynode box while in the earlier structures the hairpin wires used for support were spot welded onto the box and could lead to trouble when the tube is subjected to severe vibration.

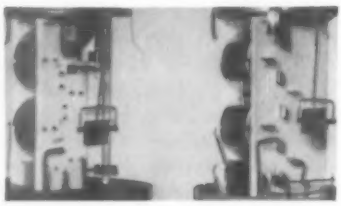


FIG. 1. Ruggedized 6292 is at right

To get ultraviolet-sensitive photocathodes (<1,800Å) we form Cs-Sb cathodes on face plates of fused silica.

An aluminum-beryllium alloy has been investigated as a secondary emitter. Multiplication is 4/stage at 200 volts against 5 for silver-magnesium.

## . . . Multialkali Photocathodes Are More Efficient

*By A. H. Sommer, RCA Laboratories, Princeton, N. J.* Of the new multialkali photocathodes (*Rev. Sci. Instr.* **26**, 725, 1955), Sb-K-Na-Cs is distinguished by very high quantum efficiency at 4,000 Å combined with a higher over-all sensitivity in the visible spectrum than has been found in any other type of cathode. This means better energy resolution and all the other advantages of improved cathode sensitivity. Its thermionic emission is of the same order as in the standard Sb-Cs cathode in spite of its high red response. This came as a surprise because, in the past, thermionic emission and long-wavelength threshold were always found to change together.

The Sb-K-Na cathode appears to be similar to the standard Sb-Cs cathode in sensitivity, but the absence of Cs should have two advantages. Firstly, thermionic emission at room temperature is lower. Secondly, in Sb-Cs photomultipliers the use of high over-all potentials (needed for high speed) is limited by breakdown above a certain voltage. This breakdown is usually attributed to cold emission from electrodes and/or ionization processes. By eliminating Cs, which has a lower work function and a higher vapor pressure than Na and K, higher voltages can be used before cold emission or ionization limits the performance.

Work on the Sb-K-Na and Sb-K-Na-Cs cathodes is still in the early stages—they are not yet used in commercially available tubes.

## . . . The 6810, A High-Gain Multiplier Phototube

*By W. Widmaier, R. W. Engstrom, R. G. Stoudenheimer, RCA Tube Division, Lancaster, Pa.* The RCA-6810 is a 14-stage head-on multiplier phototube that can deliver very high output pulse currents. The $1^1\frac{1}{16}$-in. cathode has S-11 response. The dynodes are Ag-Mg. Current gains of $10^7$–$10^8$ are possible with the 6810. Median dark current is unusually low, the equivalent of $5 \times 10^{-16}$ lumen.

Unusually high currents have been achieved in special operation. An output current of 1.2 amp was obtained with an anode supply voltage of 3,800 volts. (Present tentative max rating is 2,300 volts.) Under these conditions output is linear up to ~ 0.7 amp and saturates at 1.2 amp. These high outputs were obtained with 50% of the over-all voltage between dynode 12 and the anode. With proper voltage distribution over-all voltages could be still higher, giving even larger output.

In applications where maximum output is desired, excess voltage should be applied only to those dynodes between which space-charge saturation is likely to occur. This is because interelectrode voltages are then much higher than required for efficient production of secondary electrons.

Another way to increase output is by the introduction of additional electrodes close to the dynode surfaces (NU, Sept. '55, p. 76). With this structure it is possible to obtain peak currents in excess of 1 amp at much lower over-all voltages. Tubes of this design are now under development.

## . . . Understanding Transit-Time Spread

*By R. V. Smith, Westinghouse Research Laboratories, East Pittsburgh, Pa.* Absolute transit-time measurements have been made for illumination of $\frac{1}{16}$-in.-diameter areas at three points on the photocathodes of several photomultipliers. Light pulses of 2-mμsec rise time and 10-mμsec width at half-maximum, from a free running spark gap in $N_2$, illuminated both the photomultiplier and a 935 phototube monitor. The two output pulses were inserted into the same 125-ohm cable, adjusted to equal amplitudes (~10 volts) by suitable light attenuation, and recorded photographically on the same crt sweep. Their time difference was then read relative to a superposed 700-Mc timing sine wave. Transit time in the 935 is 0.5 mμsec.

Dividers were chosen for maximum gain, rather than minimum transit time, with the following exceptions. The 6342 shield was at first-dynode potential, although higher gain can be achieved with a potential between dynode and cathode. The 931-A divider ratios were identical with those for the 5819 and 6342, so that the difference between the 5819 or 6342 transit time and that for the 931-A at the same over-all divider voltage gives directly the cathode-first-dynode transit time in the larger tubes. The 6810 divider was as recommended: shield half-way between cathode and first dynode and focus wire connected to dynode 14.

Choice of divider influences transit time considerably. These are just representative.

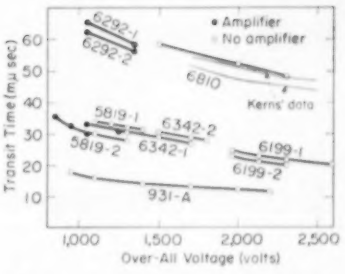



**FIG. 2. RCA 5819, 6342, and 6199, with identical dynode structures and very similar cathode-first dynode geometry, fall on a single curve, while 931-A (same dynode structure but without large cathode-dynode gap) displays same variation with voltage but about ½ the transit time. Thus photoelectron transit time represents ½ the total. RCA 6810 and DuMont 6292 show much longer transit time, as expected from their larger dynode structures**

**Transit-Time Spread**

| *Tube* | $T_{\frac{3}{8}}$-$T_0$ (mμsec) | $T_{\frac{3}{4}}$-$T_0$ (mμsec) |
|---|---|---|
| 5819-1 | 0.4 | 3.4 |
| 2 | 0.6 | 2.9 |
| 6342-1 | 0.6 | 3.8 |
| 2 | 0.8 | 3.3 |
| 6199-1 | 1.8 | 4.8* |
| 2 | 1.0 | ~2* |
| 6292-1 | 1 | 8 |
| 2 | 1 | 8 |
| 6810 | 1.2 | 7.3 |
| 6810† | 1.7 | 4.7 |

* These measurements at a radius of $\frac{5}{8}$ rather than $\frac{3}{4}$ in.

† Data of Q. Kerns, UCRL, Berkeley, Cal.

Measured transit times from the photocathode center are plotted in Fig. 2. Electron transit time in each multiplier varied as $E^{\frac{1}{2}}$.

The table lists transit-time differences for illumination at $\frac{3}{8}$ and $\frac{3}{4}$ in. from the center, at constant divider voltage. These data are averages over the voltage range shown for each tube in Fig. 2. There was no variation in transit time as a function of azimuth about the tube axis. Note that the 5819 has smaller time differences than the 6342, despite its lower voltage range and consequent longer absolute transit time. This, presumably, is because of the 5819's curved cathode, which gives a more uniform field distribution than the flat-faced 6342. The 6199, with a cathode "cup," which has both a flat end and a smaller radius-length ratio, shows still larger variations, despite its shorter transit time. The 6292 and 6810 both show surprisingly large variations at the $\frac{3}{4}$-in. radius considering that their cathode-first dynode geometry is little different than that of the 5819 or 6342.

## . . . Accelerator Grids Mean High Output

*By James S. Allen, Lawrence R. Megill, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.* To get photomultipliers with output currents >1 amp, the secondary electrons must be accelerated as rapidly as possible to decrease negative space charge near the emitting surface. Space-charge-limited current density, $J$, can be estimated using the relation

$$J = 2.3 \times 10^{-6} V^{\frac{3}{2}} d^{-2} \text{ amp/cm}^{-2}$$

which is valid for a thermionic diode with parallel plane electrodes. Obviously, $J$ can be increased by increasing the accelerating voltage $V$ and also by decreasing the distance between the surfaces, $d$.

In general, a decrease in $d$ must be paralleled by a decrease in the effective area of these surfaces. This decrease in area will limit the total maximum output current. In addition, the problem of concentrating photoelectrons from the photocathode onto the first dynode is made more difficult as the dynode's area decreases.

Because of these disadvantages, a design using an accelerating grid near the surface of each dynode was chosen. See Fig. 3. Then $d$ can be made reasonably small without a corresponding decrease in the area of each dynode.

The grids that finally evolved were formed from 90%-open woven molybdenum wire mesh. Grid-dynode spacing was 0.075 in. For a seven-stage tube, maximum output is about 1.3 amp as compared with an expected value of 2.2 amps; $J$ was 0.44 amp/cm².

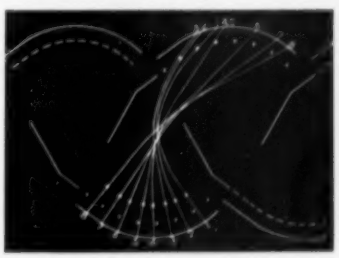


**FIG. 3. Grid-dynode system used in 7-stage multiplier. Each grid connects to following dynode. Representative electron trajectories are shown**

The estimated spread in transit time per stage was $\pm 4 \times 10^{-10}$ sec. for 400 volts/stage. A 14-stage tube would have a rise time of about $1.5 \times 10^{-9}$ sec.

# Millimicrosecond Coincidence Circuits

**Here's a review of the circuits used to measure ultrashort time intervals topped off with a discussion of the differential methods that permit measurement down to $10^{-11}$ sec**

**By Z. BAY**
*National Bureau of Standards*
*Washington, D. C.*

FAST COINCIDENCE TECHNIQUES have been developed over the past several years to measure the very short time intervals involved in nuclear phenomena, such as the lifetimes of excited states. Improvements in fast coincidence circuitry have paralleled the general rapid advance in experimental nuclear physics. This review summarizes the principal circuits used today and their development.

## Performance Parameters

The quantities of interest with respect to the performance of a coincidence circuit are as follows:

**Sensitivity, $\Delta v$.** This is the minimum voltage pulse amplitude that, when applied in coincidence to both inputs, produces a coincidence output. Because of integration $\Delta v$ is significant only if the duration of the input pulses also is given.

**Resolving time, $\tau$.** This is half the maximum time separation for which two pulses will be registered as coincident (the factor of one half is chosen to make resolving time equal to pulse length of equal-duration input pulses when defining coincidence as overlap). For varying input pulse shapes, $\tau$ is taken as the average over the pulse-shape distribution.

**Singles rejection ratio, $s$.** This is the ratio of the highest amplitude of a single that does not produce a false coincidence output, to the sensitivity.

Values for $\Delta v$, $\tau$, and $s$ are given here.

## Circuit Types

Twofold-coincidence circuits can be placed in three classes based on how they operate. The three types are outlined in the box at bottom. These are ideal types that are more or less approached by actual circuits.

The characteristics listed in the table are necessarily approximate since they depend, within limits, on the circuit parameters chosen as well as on the circuit type. Nevertheless, general conclusions on performance as a function of type are possible.

With respect to sensitivity the three types of operation are different.

Type I requires the two grids of a mixer tube to be biased to cut off so as

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### This is the Job Coincidence Circuits Must Perform . . .

Twofold coincidence circuit must take input pulses of short duration $x(t)$ and $y(t)$ (the "singles") and produce an output when those signals coincide in time. Operationally the output is $f(x,y)$ such that

$$\begin{array}{llllll} f(x,y) = 0 & \text{if} & x = 0 & \text{or} & y = 0 \\ f(x,y) \neq 0 & \text{if} & x \neq 0 & \text{and} & y \neq 0 \end{array} \qquad (1)$$

### There are Three Ways in Which This Is Done . . .

**Type I. Multiplication,** $f(x,y) \propto xy$. For example the singles are applied to the first and second grids respectively of a mixer tube. A modern version of this operation (*22*) will be discussed.

**Type II. Nonlinear addition.** The input is $x + y$, the output is

$$f(x,y) \propto \phi(x + y) - [\phi(x) + \phi(y)] \qquad (2)$$

where $\phi(x)$ with $\phi(0) = 0$, represents the operation of the nonlinear circuit element. The nonlinear elements can be either electron tubes operated near cut off or diodes.

Some of these circuits do not actually measure the difference in Eq. (2) but operate with a constant discrimination level above the output expected for singles. In this case, one has to be certain that the output for singles does not exceed the preset level and this can only be accomplished by limiting the amplitude of singles to a certain value, before reaching the nonlinear element. Thus, operation Type II, will be subdivided into Types IIa, operating with a constant discrimination level, and Type IIb, as defined by Eq. (2). Both Types IIa and IIb are widely used in fast coincidence techniques.

**Type III. Take the lesser,** $f(x,y) \propto \min(x,y)$, where $\min(x,y)$ means the lesser of $x$ and $y$. A prominent example of this type for "slow" ($\sim$1-$\mu$sec) coincidences is the diode "and-gate," widely used in computer techniques, described by Chen (*14*). Among the fast coincidence circuits the fastest and most sensitive ones are based on this type of operation.

to suppress false outputs for singles. Since the transconductance near cut off is small, $\Delta v$ is high for this type.

Type IIa uses a constant discrimination level high enough to suppress outputs from singles. A high discrimination level also suppresses coincidence outputs from small singles. Thus this type also cannot be expected to operate with small $\Delta v$.

Type IIb is better in respect to sensitivity because the instantaneous discrimination level is adapted to the input pulse heights and coincidences between small inputs are not rejected.

Type III can be expected to be the best with respect to sensitivity, because of the linear dependence of min $(x, y)$ on the lesser of $x$ and $y$.

The resolving time can be expected to be about equal to the duration of the input pulses, provided that interelectrode capacitances or other delaying effects do not appreciably slow down the operation. Since crystal diodes have lower input capacitances and lower forward resistances than electron tubes, diode circuits can be expected to be the fastest.

The singles rejection ratio depends on interelectrode capacitances and also on the match of circuit elements in bridge circuits.

Since efforts over the past few years were directed toward producing circuits with short $\tau$ and small $\Delta v$, the chronologic order of appearance of fast circuits has been roughly from type IIa to IIb to III. Type I had a relatively delayed development, probably because of lack of suitable electronic components.

## High-Speed Rossi Circuits

The first mμsec coincidence circuit, described by Bay and Papp in 1948 (*1*), is shown in Fig. 1.

The circuit is an adaptation to very short pulses of the well known Rossi circuit (*2*). The Rossi circuit makes use of the amplification provided by the two triodes in the frequency range corresponding to ~1-μsec pulse duration. The common plate resistor of the two tubes can be 100 k or higher. Due to the high amplification, the ratio of the output for coincidences to that for singles is good, ≳10.

This advantage is lost when one wants to apply the Rossi circuit to mμsec pulses. The common plate resistor has to be reduced to ~100 ohms, resulting in low gain. The

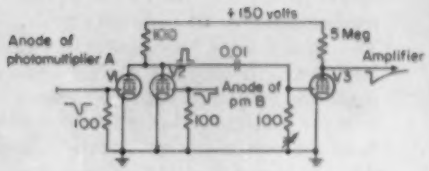



FIG. 1. Early mμsec coincidence circuit by Bay and Papp

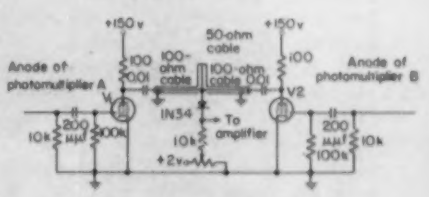



FIG. 2. Bell, Graham, and Petch's circuit. Sharply rising photomultiplier pulses cut off pentodes V1 and V2. Plate pulses of both tubes are fed into shorted-line system and then to biased discriminating and stretching diode. About 2,000 volts is applied to the 1P21 photomultipliers to get fast rise and cutoff

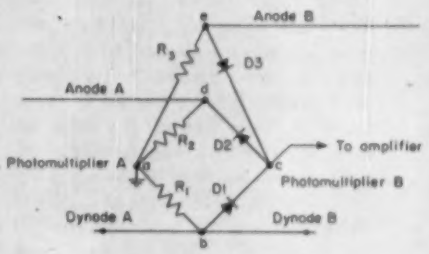



FIG. 3. Diode-bridge circuit; abcd and abce represent separate bridges that are balanced between dynode and anode pulses (of opposite sign and nearly equal size) from one photomultiplier. Diode D1 is common to the two bridges; due to its nonlinearity coincidence causes higher voltage drop across it than the sum of the voltage drops across D2 and D3. Operation is Type IIb

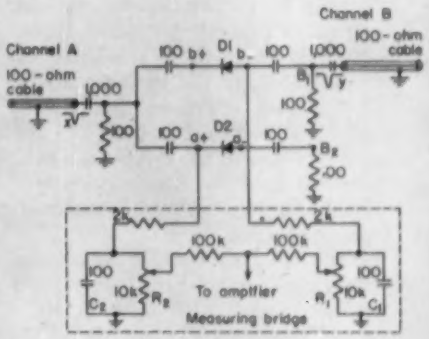



FIG. 4. Bay's diode bridge. Note that $x$-$y$ is applied across D1 and $x$ across D2. When $x > y$, current through D1 is nearly proportional to $x$-$y$. Current through D2 is proportional to $x$. Difference between these two currents is thus proportional to $y$. When $y > x$, current through D1 is essentially zero; current through D2 is still proportional to $x$. Difference between two currents is then proportional to $x$. To summarize, difference between currents in each diode is proportional to lesser of $x$ and $y$.

Current proportional to $x$-$y$ is integrated in $R_1C_1$ and current proportional to $-x$ is integrated in $R_2C_2$. Voltages across $R_1$ and $R_2$ are added and amplified

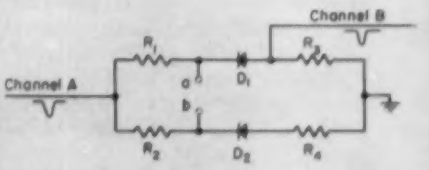



FIG. 5. Diode bridge coincidence circuit of Strauch

output merely adds the voltage swings corresponding to the separate inputs. The circuit loses its character as a coincidence circuit since it gives non-negligible output for singles. Therefore the coincidence operation is performed in the sharp-cut-off tube, *V3*, which is biased to respond only to the higher Rossi output that results for coincidences (operation is Type IIa).

Besides discrimination, tube *V3* has another important function. It stretches the output pulses to ~1 μsec duration so that they can be amplified by a conventional pulse amplifier. The stretching, of course, introduces a dead time of ~1 μsec. However, since this dead time appears only after coincidences, it causes no real loss of counts at the usual low coincidence counting rates ($<10^3$/sec) usually encountered.

Besides adding, the Rossi part of the circuit performs another and more important operation. It limits the pulse amplitudes coming to tube *V3* to a value corresponding to the cut-off of the input tubes *V1* and *V2*. Pentodes are used instead of triodes for lower interelectrode capacitances.

The resolving time of the circuit is dependent on the duration of the input pulses and was 2–5 mμsec in our experiments. Since the pentodes must be cut off, sensitivity is rather poor, $\Delta e$ ~1 volt. On the other hand, the singles rejection ratio is very high.

The short resolving time made it possible for the first time to use short cables (<1 meter) for inserted time delays in coincidence experiments.

Bell, Graham, and Petch (*3*) used a crystal diode as the nonlinear element after the Rossi circuit; see Fig. 2. For the first time in fast coincidence work they used the shorted-line techniques in which a pulse is clipped by its out-of-phase reflection.

The resolving time, dependent on the length of the shorted line, is 1–3 mμsec. Sensitivity is about 3 volts.

Bell and Petch also introduced the postcoincidence selection method that is now incorporated in almost all fast coincidence systems. Postcoincidence selection involves slow triple coincidences between the amplitude-selected singles and the fast coincidence output. Usually pulses from the last dynode are utilized for the amplitude selection. Postcoincidence selection eliminates the distortions that would be encountered in "precoincidence" selection. This is but one advantage of the postcoincidence selection method.

Another modification of the Rossi circuit for high speed is presented by Garwin (*4*) who shunts the plate load resistor of the Rossi circuit by a clamping diode in series with another resistor. The plate swing for singles is diminished thereby since the clamping diode carries current. For coincidences the clamping diode is cut off, permitting the full plate swing expected for coincidences. Since the ratio of the coincidence output to the singles output of this modified Rossi circuit is greater than two, the coincidence diode connected to the Rossi output operates from zero bias and its principal function is that of a stretcher. The resolving time obtained is around 5 mμsec the sensitivity ~3 volts. In a refinement of the circuit (*5*) the stretcher diode was biased by the d-c voltage difference appearing across the clamping diode. This permits the use of shorter input pulses ($\tau$ ~3 mμsec) for coincidences.

Meyer, Baldinger and Huber (*6*) used a Rossi circuit with a common cathode resistor. Voltage swings appearing across this resistor are fed to a biased discriminating and stretching 1N34 diode. Resolving times, $\tau$, of ~2 mμsec were obtained with $\Delta e$ ~1 volt. Since the "crosstalk" from input to output appears across the grid-to-cathode capacity, the singles rejection ratio is not as high for this circuit as for the circuits previously mentioned.

## Diode Bridges

Baldinger, Huber, and Meyer designed the first diode-bridge coincidence circuits (*7*). Typical is that in Fig. 3.

The circuit has the advantage of high sensitivity, $\Delta e$ ~0.1 volt for 10-mμsec pulses. However, it has the disadvantage of applying both anode and dynode pulses in the fast part of the circuit. The resolving time is ~10 mμsec. Operation is Type IIb, nonlinear additions.

Similar circuits have been developed by Morton and Robinson (*8*).

Diode bridge circuits of Shrader (*9*) and Lundbey (*10*) do not require the use of dynode pulses. In their circuits, point *a* of Fig. 3 is ungrounded, point *b* is grounded, and the anode pulses of the photomultipliers are fed to *d* and *e* respectively. The output appears between *a* and *c* and is fed to a difference amplifier. Resolving time is ~20 mμsec, sensitivity 0.04 volt.

## Type III Diode Bridges

The diode bridge circuits previously described operate with the sum of the two input pulses across one of the three diodes. The two-diode bridge circuit of Bay (*11*) operates instead with the difference (*x-y*) applied across one of the diodes. See Fig. 4.

The circuit of Fig. 4 can be made to handle input pulses of both polarities by connecting $B_1$ and $B_2$ through a long cable. The electrical length of the cable should be greater than the pulse duration but much less than $R_1C_1$. The output pulses are of the same sign for positive and negative inputs. This may be of importance in cases where the input pulses have tails of the opposite sign. The circuit is then powered by both the pulses and the tails.

The circuit gives resolving times corresponding to the pulse duration. (For pulses with tails of opposite sign and without the use of the long cable connection between $B_1$ and $B_2$, interference between input pulses of the opposite polarity can reduce the resolving time below the duration of the pulses. Resolving times of $\sim 3 \times 10^{-10}$ sec were obtained when using shorted lines. However this possibility was not further exploited since the differential coincidence method, described in the next section, appeared to be superior.)

The sensitivity was measured to be ~0.1 volt at $\tau$ = ~1 mμsec. With reasonably matching diodes singles re-

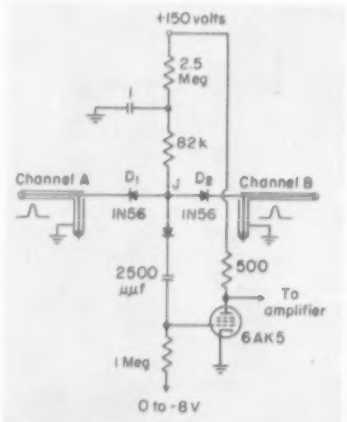



FIG. 6. Type III diode circuit. Pulse in channel A or B will cut off corresponding diode D1 or D2 causing a small rise in potential at J. Simultaneous pulses in channels A and B will cause potential at J to rise to the lesser of the two input pulses. To limit voltage swing for singles, clamping diode would be connected across 82-k resistor

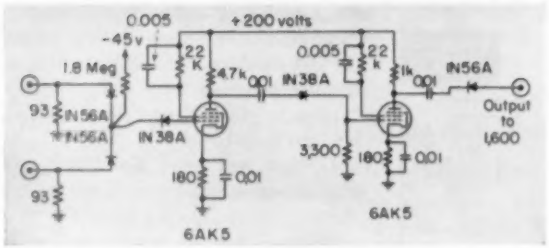



FIG. 7. Diode coincidence circuit of Minton

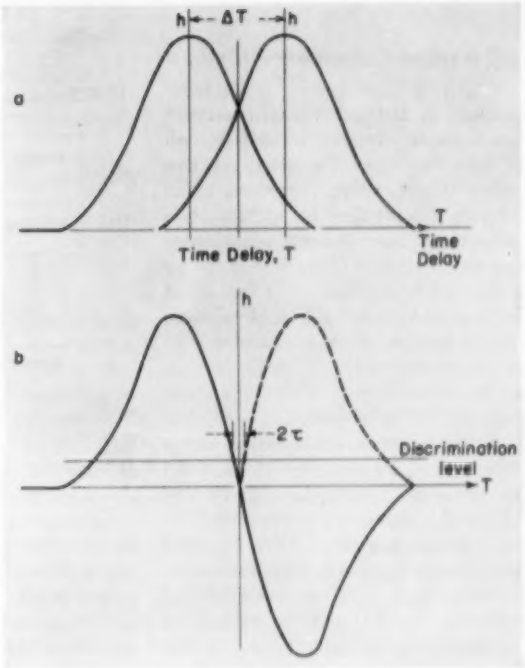
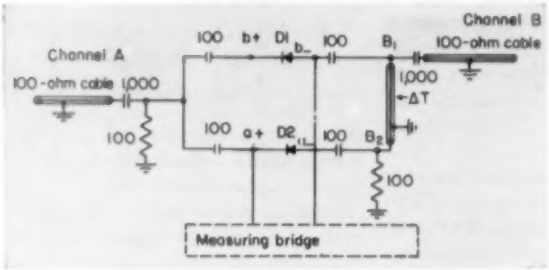



FIG. 8. Differential coincidence operation

FIG. 9. Bay's differential coincidence circuit




jection ratio can be 100 to 200.

The circuit of Strauch (*12*), based on an idea by Neher (*13*), operates like that of Fig. 4. Instead of utilizing the charges developed, Strauch measures the potential difference between points *a* and *b* in Fig. 5. Since both potentials are different from zero during a coincidence, a difference amplifier is needed. The circuit was operated with a resolving time ~10 mμsec and $\Delta v \sim 0.3$ volt.

## Other Diode Circuits

The well known crystal-diode coincidence circuit used in computer techniques for μsec pulses (*14*) has been adapted to moderate speed ($\tau \sim 0.5$ μsec) by Elmore (*15*). DeBenedetti and Richings' circuit (*16*) for the mμsec region is shown in Fig. 6; operation is Type III.

The problem of applying the low-speed computer "and-gates" for high-speed coincidences raises questions similar to those encountered with Rossi circuits when applying them to high speed. The singles rejection ratio of the circuits is quite low if the pulse duration is small and therefore there is need for a discriminating diode, having a high-speed input and a relatively low-speed output (stretcher diode). Due to the small voltage swings developed at the common junction of diodes D1 and D2, a clamping diode is not required.

DeBenedetti's circuit has good resolution (~1 mμsec when used with shorted lines) and sensitivity (a few tenths of a volt). A circuit of this type, modified by G. Minton (*17*) gives a sensitivity of 0.3 volt for 2.5-mμsec input pulses and a singles rejection ratio ~30. The circuit is shown in Fig. 7.

Madey's modification (*18*) has $\tau \sim 3$ mμsec and $\Delta v \sim 1$ volt.

## Multiplication Circuits

Schultz and Beringer (*19*) used a 6AC7 pentode to multiply two ~1-μsec blocking-oscillator pulses fed to control and screen grids. Resolving time is ~15 mμsec. Wiegand (*20*) used scintillation counters as detectors and pentagrid converters for mixing. The principle of the distributed amplifier is applied by using a series of tubes. Resolving time is about 10 mμsec.

The recently developed 6BN6 gated-beam tube proved to be very suitable for fast coincidence work. After its first use (1951) for coincidences by Smaller and Avery (*21*) with moderate speed ($\tau \sim 20$ mμsec), Fisher and Marshall (*22*) made a detailed investigation of the performance of the tube for fast coincidence techniques.

Positive pulses are fed to the two control grids, which are normally biased to cut off. The coincidence output appears across the plate load resistor and is further amplified. The resolving time is dependent on the duration of the input pulses. With input pulses from a mercury-switch pulser the resolving time $\tau = 3 \times 10^{-10}$ sec was obtained, i.e., the time resolution is not limited by the resolving ability of the tube itself. The sensitivity is $\Delta v \sim 2$ volt for input pulses of a few mμsec duration.

The 6BN6 circuit of Fischer and Marshall was adapted by Neilson and James (*23*) for a neutron time-of-flight spectrometer.

Cathode-ray-tube coincidence circuits, in which the detector singles $x$ and $y$ are fed to the horizontal and vertical deflection plates of an oscilloscope and an output is recorded only if the spot leaves the $x$ or $y$ axes, are also Type III (at least for small deflections). Though these circuits (*24, 25, 26*) have resulted in resolving times down

to 2–3 × $10^{-19}$ sec, they will not be discussed further here.

## Differential Coincidence Method

Resolving time can be made independent of the pulse length without loss in sensitivity (*28*). The definition of coincidence as "overlap" of two pulses is qualitative. One can make it more quantitative by utilizing two outputs of two separate coincidence circuits, displaced from each other by a constant time delay. The final result is then obtained by a null method. The definition of coincidence is thus based, instead of merely on the overlap, on the time difference (phase difference) between the input pulses.

In Fig. 8a the curves of output versus delay time, $T$, are plotted as given for the same input pulse pair by two identical circuits with a time delay $\Delta T$ inserted between them. Fig. 8b shows the difference of the two outputs as obtained with a difference amplifier and with the negative output inverted as indicated by the dotted line. For low discrimination level, an output appears in practically the entire range of overlap of the input pulses, except in a small gap around the middle of the range.

Now one can use the output pulses of one of the two coincidence circuits, introduce them into an anticoincidence gate that is operated by the difference output such that the coincidences are rejected if there is a difference output. In this way a resolving time results that is equal to half of the gap width.

Experiments have shown that resolving times, two orders of magnitude smaller than the pulse length are easily obtained. This short resolving time is accomplished with low discrimination levels so that there is no sacrifice in sensitivity. On the contrary, the sensitivity for the entire operation can be improved. Since $\tau$ is practically independent of the pulse length, there is no objection to the use of amplifiers between the detectors and coincidence input; therefore small detector pulses can also be utilized for coincidences, even with circuits of relatively poor sensitivity.

The differential coincidence operation can be performed with any type of coincidence circuit. The circuit used by Bay to obtain the differential output is shown in Fig. 9. This is a simplified circuit that takes the place of two of the circuits shown in Fig. 4.

The circuit of Fig. 4 performs the arithmetical operation $(x - y) - x$. A second such circuit in which the one channel is delayed by $\Delta T$ will perform the operation $(x - y)_{\Delta T} - x$. When the difference between these two outputs is taken, it is readily seen that the $-x$ operation is unnecessary in the two circuits. Therefore the D2 channel of Fig. 4 can be omitted and 2 channels corresponding to the D1 channel can be combined as in Fig. 9 to perform the difference operation. The time delay $\Delta T$ is inserted between $B_1$ and $B_2$. The length of $\Delta T$ is not critical, except that it should be a fraction of the duration of the input pulses.

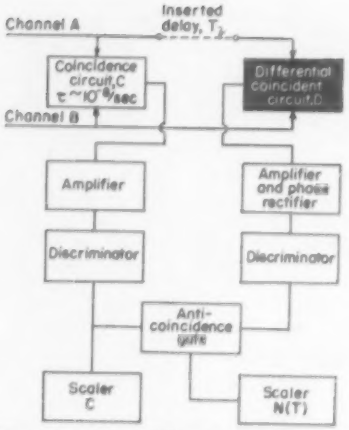



FIG. 10. Bay's differential coincidence system

Since two charges of the opposite sign are utilized in this circuit as well as in the circuit of Fig. 4 the measuring bridge is the same as in Fig. 4 and there is no need for a difference amplifier. A phase rectifier is applied after the amplifier to invert pulses of negative sign into pulses of positive sign. The output pulses are fed into a discriminator. The resolving time can be readily varied and properly chosen by setting the discrimination level. A lower discrimination level corresponds to a shorter $\tau$. With input pulses of the duration of ~10 mμsec, resolving times have been as short as 0.1 mμsec.

The block diagram of the equipment is shown in Fig. 10. A separate coincidence circuit, $C$, with a sufficiently long resolving time (~$10^{-8}$ sec) to respond to all coincidences irrespective of time delays that can occur in the experiment gives the total coincidence counting rate, monitors the equipment, and provides for a normalization factor. The output of the anticoincidence gate versus the time delay $T$ inserted before the differential coincidence circuit $D$ gives the fast coincidence curve. Instead of the anticoincidence gate an "and-gate" can be used in which case the fast curve is obtained by subtracting the counting rate given by the "and-gate" from the total coincidence rate given by $C$.

Another version of the differential coincidence method was used by G. Minton (*17*). In his circuit the two coincidence outputs are fed to a slow coincidence circuit (1-μsec "and-gate"), the output of which gives the fast coincidence curve. The resulting resolving time $\tau_r$ is given as $\tau_r = \tau - \frac{\Delta T}{2}$ where $\Delta T$ is the time delay inserted between the two coincidence circuits and $\tau$ is the resolving time of the two identical circuits. To maintain efficiency, $\frac{\Delta T}{2}$ should not be larger than the smallest $\tau$ corresponding to the smallest pulses of the amplitude distribution. The resolving times reported by Minton are of the same order as those obtained by Bay, et al.

How to analyze coincidence data from these differential circuits is discussed in the complete paper to be published in the IRE Transactions on Nuclear Science.

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# Today's Pulse-Height Analyzers

## A review of current developments that result from wide application of kicksorters to problems of physics, chemistry, medicine, and industry

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KICKSORTERS* ARE no longer rare in research laboratories. They are beginning to be used for routine chemical analysis, for logging oil wells, and for other commercial applications. Single- and multichannel analyzers are used for certain routine counting operations such as liquid scintillation counting (*1*) and medical diagnosis (*2*).

Developed for use in nuclear research, these devices are high-speed electronic sorting machines used with proportional counters, ion chambers, and scintillation counters. Their development has gone on in parallel with that of analog-to-digital converters, and the instrument designer must be acquainted with progress in allied fields so as to take advantage of the latest techniques.

Kicksorters can be classified in several different ways. For example, there are single- and multichannel analyzers. There are analyzers that sort directly into channels by amplitude, and those that first convert pulse height to a proportional time interval. The sorting may employ threshold trigger circuits, cathode-ray tubes or beam-deflection devices. The data may be accumulated in scalers, in digital memory devices, or on photographic film (*4, 5*).

### Single Channel Analyzers

Investigators recently seem to have been preoccupied with multichannel instruments. Most of the single-channel instruments now available were designed before 1952. There are two new ideas that I think merit consideration for use in single-channel analyzers. One of these was employed in a 20-channel analyzer (*6*). It uses one discriminator per channel. Each input pulse is stretched for a short time. During the stretch interval a step pulse of fixed amplitude is added and a count is recorded if the added step causes a discriminator to trigger. In this way the channel width depends on the added step rather than on the difference between two discriminator settings.

The other innovation is the low-level discriminator developed by Kandiah (*7*), that gives stable operation with a threshold as low as 0.01 volts. This might operate directly from the output of a photomultiplier tube.

### Multichannel Analyzers

There are many different types of multichannel analyzers to choose from with different characteristics and ranging in price from perhaps $1,000 to $20,000. Original models used a series of discriminator circuits biased at increasing voltage levels and anticoincidence circuits to indicate, for each incident pulse, the highest discriminator fired. There are problems in design of such analyzers (*4*). Current models employ an expander or window amplifier that feeds a group of up to 20 discriminators. The window amplifier makes the channel width problem less serious. The most elaborate analyzer of this type is the Oak Ridge MC-5, which uses six window amplifiers to cover 120 channels. Its minimum dead time is 1.6 $\mu$sec plus the pulse width. Each channel has a scale of 16 and a fast count register (60/sec). This instrument must be carefully aligned with the aid of a sliding pulser. Thanks to good engineering, it is fast, stable, and reliable.

D. H. Wilkinson made a big contribution to the field when he suggested converting the pulse-height measurement into a time measurement (*8*). And the next big step was taken by Hutchinson and Scarrott who coupled this technique with digital computer data storage (*9*). Most recent activity has been based on the work of these three men.

### Wilkinson-type Kicksorters

The pulse-height-to-time conversion can be effected in several ways. In the Wilkinson analyzer a capacitor is charged to the peak amplitude of the input pulse and then linearly discharged with a constant current. During the discharge time pulses from an oscillator are passed into an electronic counter. The number of pulses fed into the counter determines the channel in which the pulse is to be tallied. It is not difficult to achieve good linearity in charging and discharging the capacitor, thus obtaining linear response and uniform channel widths. Channel width stability is also good, and there is no problem of gaps or overlap between channels. The disadvantage is the dead time associated with analysis of each pulse. In Wilkinson's kicksorter the counts were tallied on telephone-message registers that limited the speed to 10 counts/sec; 70 tubes were used for 99 channels.

Magnetic core kicksorters developed at Los Alamos and Argonne National Laboratories are very similar in operation except that counts are tallied in a magnetic core memory (*10*). The Argonne analyzer has 256 channels and a dead time that varies with the pulse height, but averages about 80 $\mu$sec.

The latest Los Alamos model has 100 channels and an average dead time of 70 $\mu$sec. They have added temporary analog storage for the first pulse that arrives while another pulse is being analyzed. This reduces the counting loss to 1% at 1,000 pulses per second although it is less useful at higher rates.

### Serial-Memory Kicksorters

Hutchinson and Scarrott store the data as binary coded numbers serially

* Pulse-height analyzer is rather clumsy, so, with the reader's indulgence, I will use the descriptive British term kicksorter.

in an acoustic delay line. The stored information circulates around a closed loop with a period equal to the delay of the acoustic line. This instrument requires a high-quality pulse stretcher since incoming pulses may arrive at any phase of the circulating memory. The average dead time is relatively long, being equal to half the delay line period. On the other hand, the cost of this type of storage system is considerably less than the cost of a magnetic core memory. The British used mercury delay lines in the first instrument and presently are using nickel wire lines. The latter are cheap but limited to a bit spacing of about 1 μsec. Similar analyzers have been built in this country using fused quartz lines that can store five to ten times as many bits per unit of time (*11, 12*). Schultz and Pieper, at Yale, have used 0.2-μsec spacing in a 1-msec line to store 1,024 counts in each of 500 channels. They provide a continuous analog display on a cathode-ray tube and facilities for automatically plotting the data on a strip-chart recorder at the end of a run. Gallagher and McKibben store the numbers in binary-decimal notation. Using 0.5-μsec spacing and a 1-msec line, they store up to $10^5$ counts in each of 100 channels. The binary-decimal storage makes it convenient to print the data automatically with a solenoid operated adding machine.

As Hutchinson has pointed out (*3*), a continuous display of the data is extremely useful. This is supplied, with little extra circuitry, in all of the kicksorters using digital storage. Many of the present kicksorters display the binary numbers stored in the channels. Often the data are read visually from such a display. However, an analog display is much easier to interpret and is preferable for those machines that have automatic printout.

It should be noted that the same types of data storage are presently being used in neutron time-of-flight spectrometer applications (*13*). Watkins (*14*) and Glenn (*15, 16*) have described ten-channel analyzers using special beam-deflection tubes. This approach proved to be less satisfactory than the conventional multidiscriminator circuits. Recently we used one of these beam deflection tubes in a kicksorter that will handle pulses less than 0.1 μsec apart. However, I think the pulse storage technique, which I will refer to later, is a better solution.

## General Characteristics

*Desirable qualities for kicksorters include speed, linearity, resolution, and stability compatible with the rest of the system.*

*Pulses from ionization chambers may have a rise time of several milliseconds while some scintillation detectors have a rise time in the millimicrosecond region. At present the principal interest is in the region of 0.1–10-μsec rise time. Even with well shaped pulses these speeds demand much of the sorting circuits. Speed also enters in counting rate.*

*The channel width or the number of channels desired will depend on the resolution of the detector. Even under optimum conditions the best resolution achieved with scintillation counters is in the neighborhood of 5%. On this basis, 100–200 channels would seem to be adequate for use with scintillation counters. But in ionization chamber measurements of energetic alpha particles one may obtain resolution of less than 1% so narrower channels may be useful in some cases.*

*Linearity involves two factors. First, the location of the channel or channels should be linear in terms of amplitude (energy). Second, the channel width should be the same regardless of its location in a single channel instrument; the channels of a multichannel analyzer should be equal. Uniformity and stability of channel width should be 1% or better, since one may wish to compare pulse height to this accuracy. Linearity and stability of position should be in the order of 0.1% if the kicksorter is not to degrade the pulse-height information available from a high-quality detector-amplifier combination. The stability figures refer to a period of several hours, which is often the period of time required to run an experiment. Channel-width uniformity and stability are particularly difficult to achieve in those instruments that make use of separate trigger circuits to establish the channel boundaries. The problem is less serious in certain other types of multichannel analyzers.*

Beam-deflection techniques have been employed for analog-to-digital conversion of pulse height (*17, 18*). Porter and Borkowski use a cathode-ray tube that has a ladder-shaped target with equal width bars and spaces. The beam is turned on at the peak of the pulse and generates a train of pulses proportional to pulse height as the beam sweeps back to the baseline. The pulse train establishes an address configuration in a counter, in the manner of Wilkinson's kicksorter. Linearity and channel widths are determined by the cathode-ray tube and its circuits. This method seems to have no important advantages over the Wilkinson method at present.

## Photographic Methods

First among photographic techniques is the old method of photographing the pulses displayed on a cathode-ray oscilloscope with triggered sweep. This is cheap, easy, and often good enough for survey work. One can determine energy or location of spectral lines in this way but can make only rough intensity measurements.

A considerable improvement is achieved by stretching the pulses and photographing through a gray wedge (*19, 20, 21, 22*). The developed photograph presents log of counting rate as a function of pulse height or energy (Fig. 1). The energy scale can be made linear, and energy resolution is adequate for use with scintillation counters. They have been built with an expander or window amplifier where higher resolution was desired. A fast sweep may be used for high counting rates and a slow sweep for low ones. We have found them very useful for survey work. Using a Polaroid camera and film, the record is obtained as fast as data can be printed out of computer-storage machines. Better intensity information is obtained by using spectrographic film, and printing on high contrast paper. Processing the film is a nuisance, and the data are not as precise as those obtained with conventional kicksorters, but the equipment is simple and considerably cheaper than other multichannel instruments. Gray-wedge analyzers should be of interest to the less affluent laboratory and the person who needs a portable multichannel analyzer.

Recently Maeder (*23*) has described modifications of this instrument to ob-

tain a linear record of the counting rate or to make the energy scale logarithmic. A linear energy scale is easy to work with but not the most efficient way to deploy a given number of channels (*24*).

Several people have photographed individual pulse heights on a film that moves past the cathode ray tube (*25, 26, 27*). A serious objection to this method is the time required to process and scan the film. For good results the scanning equipment must be very precisely built, so that the difference in cost between this type of kicksorter and a Hutchinson-Scarrott instrument actually may not amount to much.

## Pulse Stretcher

A high quality pulse stretcher is an essential component for several of the kicksorters mentioned above, the Hutchinson-Scarrott and the gray-wedge models, for example. This might consist of a low-impedance driver stage, a diode for charging, a capacitor for storing, and a gated discharge tube. Germanium diodes do not have a high enough ratio of forward-to-back resistance, and the silicon diodes that might be suitable in this respect do not have necessary switching speeds. Tube diodes do not have a sharp cutoff; their shunt capacity is appreciable, and there may be hum pickup from the heater. Stretcher circuits with inverse feedback have been developed at Brookhaven and at Oak Ridge to overcome these diode limitations and to achieve fast and linear operation. A Brookhaven circuit used in a gray-wedge kicksorter employs five tubes to amplify, stretch, and block the input.

FIG. 1. Spectrum of $Cs^{137}$, gray-wedge analyzer photograph

## Amplifier

Linearity and stability of the kicksorters that convert pulse height to time is so good that the pulse amplifier and radiation detector are now the limiting components. Most pulse amplifiers available today are neither very linear nor very stable. It is customary to use negative feedback to achieve these ends. There are two difficulties. First, carbon resistors, even "stabilized" carbon resistors, have a relatively high temperature coefficient and their value may drift for hours after a set has been turned on. Another difficulty is that one often tries to use an amplifier with short clipped pulses so that the significant frequencies are high; the gain of the amplifier stages is considerably lower than the designer has anticipated; and the feedback can do very little to stabilize the gain. This problem is most serious for the output stage, which may be expected to deliver a 100-volt pulse in a few tenths of a microsecond. Many people would like to operate at even higher speeds.

Amplifier overload is another serious problem with scintillation and proportional counters. This has been discussed in the literature (*28, 29*).

## Duty Cycle

A third problem is the question of duty cycle. This is particularly acute when the source intensity fluctuates as with pulsed accelerators. E. Fairstein of Oak Ridge has developed a double-delay-line amplifier that shapes the pulses so that the area below the baseline is equal to that above (*30*). This is not an easy amplifier to construct or to adjust. At Brookhaven we have used a short *RC* differentiation at the scintillation counter and an equal *RC* differentiation near the middle of the amplifier to achieve the same result. Fairstein uses a delay line which is long enough to permit the negative feedback to be effective in stabilizing the amplifier. A flat topped pulse is a desirable shape for kicksorter analysis. No particular arrangement of delay lines or time constants will be suitable for all types of problem. The type and location in the amplifier of RC or line shaping devices is always a compromise and often not a propitious one. Thus a precision pulse calibrator is essential.

## Calibration

*It is important to have a precision pulse calibrator associated with a scintillation spectrometer. Shape of the calibration pulse should be similar to that from the detector, since amplifier and kicksorter may respond differently to different pulse shapes. Additional checks are needed to have confidence in a scintillation spectrometer system. A cross check between the pulse calibrator and several sources of known energy is an obvious step. The sources of known energy may be used at different distances from the detector to see whether the system is rate dependent. Another useful experiment is to connect calibrator and detector to the system, in parallel, and to observe the shape of the line from the calibrator in the presence of a low counting rate and a high counting rate from the detector.*

## Counting Rate Problems

It should be noted that most of the kicksorters described here have a relatively long deadtime. It might seem that this is not important since one can accumulate a large number of pulses in a few minutes at relatively low counting rates with a 100-channel instrument. However one may wish to measure the intensity of a weak line in the presence of a strong one, in which case one may have to count millions of pulses in order to get a good statistical sample of the small pulse. A more serious problem is measuring a rapidly decaying source. Time-correlated events may give spurious results.

If the deadtime is long, one will often wish to operate with a large counting loss. In most of the height-to-time conversion kicksorters the dead time varies from pulse to pulse so that it may be difficult to correct for counting loss at high input rates. The dead time is proportional to the pulse height in the Wilkinson and magnetic core kicksorters, so that the total dead time, for a data run, depends somewhat on the spectral distribution as well as the number of counts. Johnstone has recently added a meter to the Los Alamos core analyzer to indicate the average counting loss. Kicksorters using delay line storage may have a fixed or a variable dead time. The Los Alamos circuit may record more than one pulse in a delay line period if the successive pulses increase in height. This gives an aver-

age dead time of half the delay line period, which is independent of the spectral distribution provided the pulses are not correlated.

## Pulsed Accelerators

I think that the most difficult problem today is that posed by pulsed accelerators. The accelerators are expensive; their duty cycle is low; and a high premium is attached to making maximum use of the beam during the short interval it is on. Cerenkov or liquid-scintillation counters have a pulse-rise time of a few millimicroseconds. However amplifiers and kicksorters that would operate with 0.1-μsec pulse spacing would be quite a boon. Inverse feedback cannot be used in connection with distributed amplifiers so that one is forced to consider the linearity and stability of amplifier tubes. It would be nice if the output of photomultipliers could be raised and the sensitivity of discriminators brought down so that amplifiers could be eliminated. But this would not solve all the problems. It is hard to conceive of a multichannel sorter to operate at these speeds which would have good linearity and stable channel widths. If that hurdle can be surmounted, fast scaler circuits or memory devices to store the data are not presently available.

The most promising scheme is that developed by Cunningham and improved by Reeves at the National Bureau of Standards (*31*). Here the several pulses which occur during one burst of radiation are recorded in analog fashion on the face of a cathode-ray tube and cause a redistribution of the charge on the tube face. The same pulses may then be "read off," one at a time, while the accelerator beam is off and analyzed by conventional techniques at reasonable speeds. This technique of temporary analog storage employs the same properties of cathode-ray tubes as does the Williams system of cathode-ray-tube digital storage. Cunningham states that 3-mμsec pulses have been analyzed and possibly several hundred pulses could be stored during a single accelerator burst.

## Coincidence Control

A simple gamma-ray spectrometer consists of a scintillation detector, an amplifier, and a kicksorter. Because only part of the gamma-ray energy may be dissipated in the scintillator, the spectrum obtained from a monoenergetic source is quite complex.

Various schemes are employed to improve the response. One may surround one scintillation detector with another and record only those events which produce light in the inner phosphor (*32*). In this case the kicksorter will be connected to the inner phosphor and gated off by signals from the outer phosphor. Other techniques make use of multiple phosphors and coincidence circuits to select for recording those events that produce a Compton-scattered electron in a selected solid angle or give rise to pair production. In any of these cases only a small fraction of the total number of pulses will be selected for display. Consequently a means of gating the kicksorter is required and circuits up to this gate should be able to handle very high counting rates without distortion. Other research problems require similar configurations involving control of the kicksorter by the signals from auxiliary detectors.

## Choosing A Kicksorter

I think it is only fair to acknowledge that construction of any of the multichannel kicksorters is a big and difficult job. The analyzers with digital memories are especially complicated. The circuits which have been developed to date are simple enough in principle but tricky in practice. More engineering and more new ideas are still needed to reduce the cost and increase the reliability. However no amount of engineering will guarantee that the instruments may not be misused.

In choosing a kicksorter a person should consider the cost and performance of the system as a whole. A detector, amplifier, and high voltage supply may cost about $1,000. A single-channel analyzer and scaler cost about as much more.

A single channel with automatic scanning mechanism and recorder will cost about $2,000. A gray-wedge system is in the same price region. A combination of single-channel and gray-wedge kicksorters permits rapid survey and precise measurements in regions of interest. Probably the delay-line analyzers are next higher in cost. At present the magnetic core analyzers are roughly twice as expensive as the delay line—both having visual display and automatic data printout. A twenty-channel discriminator kicksorter with amplifier and calibration-pulse generator is slightly more expensive than the delay-line type.

Auxiliary equipment, such as scintillation detectors, amplifiers, single-channel selectors, coincidence circuits, and so forth may cost several thousand dollars. When one takes them into account, the kicksorter cost is not so frightening.

## For the Future

*I hope that kicksorters will become more reliable and cheaper. Use of digital computer techniques has obvious advantages and will contribute much to this field. Transistors should help to reduce size and increase dependability. The temporary-storage technique for use with pulsed accelerators merits wider consideration. It would be a mistake to concentrate our attention on the kicksorters alone. They are a lot of fun. But detectors and amplifiers must receive attention too.*

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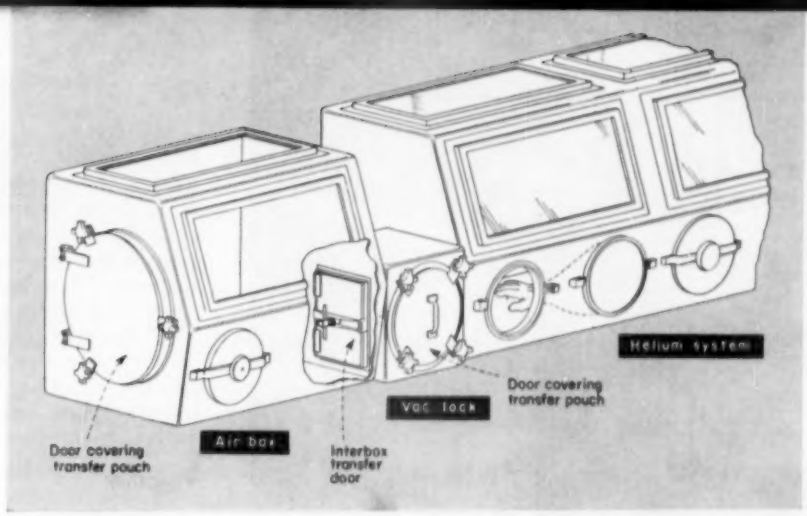


FIG. 1. Interconnecting glovebox and vacuum-lock arrangement in Research Laboratory

# Handling Alpha-Active, Pyrophoric Materials

## 2—Glovebox Design and Construction

**Careful glovebox design and fabrication assure more reliable leaktightness than does caulking. Gloves, possibly the weakest part of the system, should emphasize quality, rather than frequent changes, to avoid spreading contamination**

By L. R. KELMAN, W. D. WILKINSON, A. B. SHUCK, and R. C. GOERTZ
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MOST GLOVEBOXES are designed as single-operator enclosures with glove ports on one side only. If the operator must reach everywhere in the enclosure, then the entire inner space must be within about 24 in. of a glove port. The 30-in.-deep gloveboxes used at some installations require tongs or other means of extending the operator's reach.

Unless larger boxes are needed, there are some advantages to small boxes. In addition to assuring easy access to all parts of the box, smaller boxes mean more rigidity, and the shorter welds mean fewer chances of leaks. Also, smaller gas volumes need be purified where an inert atmosphere is used. But small gloveboxes never seem to have enough shelf or storage space.

In the ANL Plutonium Metallurgy Research Laboratory, most gloveboxes are a maximum of 24 in. deep, governed by the small equipment used and limited space available (see Fig. 1). Where extra depth is desired, two such boxes are placed back to back.

The large, heavy equipment in the ANL Fuel Fabrication Facility requires large, sturdy enclosures. Accordingly, a flexible design was developed (Fig. 2), using a strong rigid frame with heavy-plate panel inserts in place of the usual light sheet-metal construction. Wherever possible, heavy equipment is supported from the floor on independent bases. Standard components can be built up modularly to house almost any size equipment, ranging from balances and delicate measuring apparatus to rolling mills and hydraulic presses. Standardized gaskets, flanges, bolt locations, etc., allow interchangeable end plates, window gaskets, window retainers, and the coupling of gloveboxes into an interconnecting system. A 36-in.-long module is used with an interglove spacing (center to center) of 18 in. In addition, there are 72-in.-long double modules, but the windows, glove spacing, and most of the components are standard in size. By designing the hoods for operation from two sides, it is possible to increase the hood width to 48 in. so that equipment is accessible from both sides.

Three basic glovebox modules have been adopted to meet about 85% of the enclosure requirements in this facility: basic low and high modules—36 in. long, 48 in. wide, and 48 and 71 in.

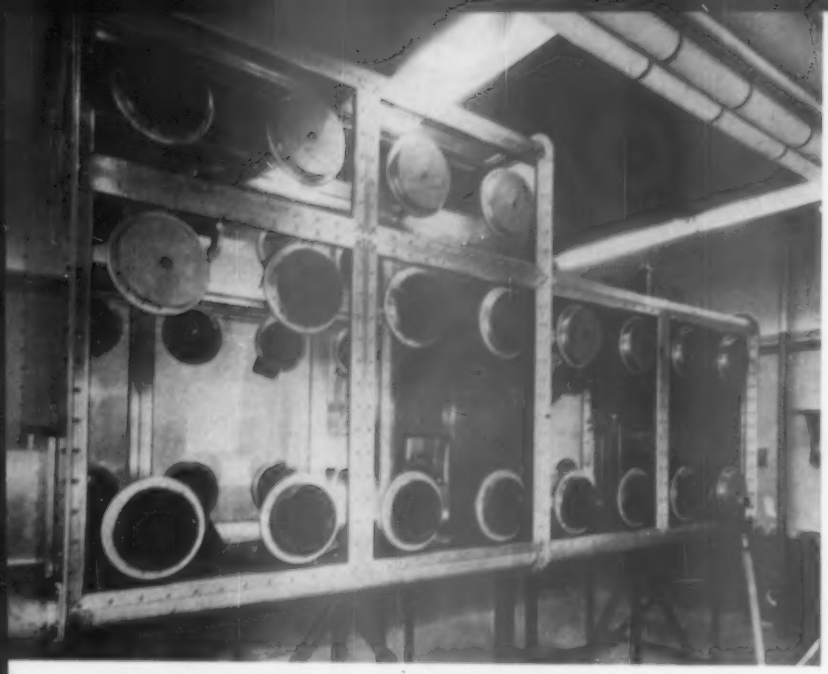

FIG. 2. Prototype fuel-fabrication-facility gloveboxes

high, respectively; and a transfer module—36 in. long, 30 in. wide, and 32 in. high. The latter is used primarily for transferring material to a 100-ft backbone conveyor tunnel. The 48-in.-high boxes have two tiers of gloves; the 71-in.-high, three tiers.

## Materials

The Research Laboratory gloveboxes are fabricated from 14-gage type-304 stainless-steel sheet. It is readily fabricated and welded, provides excellent corrosion resistance, and is easy to clean, especially since stainless steel permits acid cleaning of contamination.

The hard aluminum alloys have the best properties for the fuel-fabrication facility. They are less costly and more easily fabricated than the type-304 stainless steel, and they have sufficient corrosion resistance for most of the anticipated applications. Resistance to strongly corrosive atmospheres in the few places where they may be encountered will be obtained by protective paints and plastic coatings. Large, high-surface-finish aluminum plates can be obtained for floor plates, partitions, and service panels. Fasteners for gasketing materials are stainless steel. Tapped holes in the aluminum are reinforced by stainless-steel thread inserts.

**Windows.** Whether to use glass or plastic windows depends on the plastic and glass being considered and on the application. Safety glass, used for the glovebox windows of the Research Laboratory, remains clear and smooth and is easy to wipe clean. As it is relatively inflexible, it requires a flat seating surface or it is apt to crack when tightened. If it cracks, the crack does not go all the way through and, thus, does not necessarily present a leak. Safety glass is relatively impermeable to gases, and systems with safety-glass windows are easier to purge and clean than those with plastics.

The plastics most commonly used for glovebox windows are Lucite and CR-39, an allyl polymer. The windows of the Fuel Fabrication Facility are clear, transparent, cast CR-39, which has a high degree of resistance to scratching, impact, stress crazing, and chemical attack. Lucite has the advantage that it conforms most readily to slightly curved seating surfaces without cracking and it does not chip or crack on slight impact as readily as does glass. Lucite also is easy to machine, whereas CR-39 plastic is considerably harder to machine. Lucite's disadvantages are that its surface becomes easily scratched and roughened, oils and other organics that might be used in gloveboxes tend to cloud its surface, it tends to flow where clamped, it is permeable to helium, hydrogen, and moisture, and it ruptures comparatively easily on heavy impacts and explosions.

**Plastics and synthetic rubbers.** There is concern about using plastics and synthetic rubbers in glovebox systems of the type under consideration because they are less than perfect and subject to failure. But there are places where they must be used for want of a better material. Such places include window and glovebox gaskets, other seals, gloves, control-instrument diaphragms, and transfer pouches. Neoprene is used in gloves, and type GN neoprene with antioxidant additive is used extensively for gasketing material. Vinyl-plastic (polyvinylchloride) transfer pouches are used in both plutonium facilities at ANL. Polyethylene and cellophane have been used for similar applications at other installations.

## Visibility

The degree of visibility is important to safe glovebox practice. For the sheet-metal glovebox where the windows are only part of the front face, there are blind areas on the floor near the front wall if vertical walls and windows are used.

This difficulty is avoided in the Research Laboratory gloveboxes by designing the windows to slope out from the top with the lower sheet-metal portion of the wall sloping out from the bottom as shown in Fig. 1. The glove ports are welded into the lower sheet-metal section. The sloping box front enables more comfortable observation.

The Fuel Fabrication Facility type of glovebox (Fig. 2) uses windows that extend practically to the box floor. The glove ports are gasketed into the windows. This approach sacrifices some working comfort while the operator is close to the box.

## Tightness

Gloveboxes must be essentially gastight both to protect against contamination leakage and for economic maintenance of inert atmospheres. To achieve tightness to a helium-sensitive mass-spectrometer leak detector requires careful joining and gasketing techniques such as are used ordinarily in high-vacuum work (*1*). The tightness depends on design and effort.

**Part 1**
of this series (March '56, p. 61) was "What is the Best Approach?"

**Part 3**
the last of the series, will cover "Ventilation of Gloveboxes."

**Gaskets.** Unrestrained flat gaskets are standard for most gloveboxes. They are not dependable in that the large amount of deformation needed to achieve tightness often causes lateral slippage. A gasket design was developed for the Research Laboratory that would remain tight despite vibrations and normal flexing of box walls.

Standard O-ring gaskets make excellent tight seals and are recommended wherever possible. Unfortunately glovebox windows and walls are usually rectangular, making it difficult and expensive to round the corners of the gasket grooves so as to achieve a tight seal with a continuous standard O-ring. Very promising results have been obtained recently in experiments with mitered and vulcanized square-cornered O-rings fitted into rectangular milled grooves.

It is important that, when the box is being constructed, leaktightness be achieved without caulking or sealing compounds or mastic tapes. Once such materials are used there is no turning back and often leak tightness is never achieved. The effort necessary to repolish seating surfaces, to remove all cross scratches, and to examine and correct for gasket defects usually proves to be well worthwhile. The time to use sealing compounds or mastics is when a leak develops after the system is contaminated and there is no other solution. The vacuum technique of applying to the gasket a thin layer of vacuum grease, such as Apiezon N, is recommended for leaktight joints.

**Auxiliary openings.** Seals on fixed tubes, rods, or wires and on shafts for transmitting motion must receive considerable attention for adequate tightness. In general, vacuum techniques (*1*) are adequate provided allowance is made for contamination that might get into the room when withdrawing a contaminated shaft through a seal.

Extra openings should be provided for such items as insulated electrical leads, movable shafts, or tubing. Such openings are often difficult to make after welded-sheet-metal gloveboxes have been completed without influencing their tightness. They are especially difficult to make after plutonium contamination. Figure 3 illustrates three types of openings that are provided with O-ring gasketed covers on the inside and outside of the glovebox.

Removable aluminum-plate panels, which are gasketed to the glovebox frame, simplify introducing extra openings in the fabrication facility.

A safe, permanent seal is not easily made for a rapidly turning shaft. Precisely fitting O-rings have sometimes given excellent service on highly finished rotating shafts, but it is difficult to ascertain in advance whether or not the desired conditions have been attained. Some chevron seals, dynamic grease seals, and bellows-sealed wobble shafts also have given good service, but their reliability is always open to question. If rotary-shaft seals are required, the driving motor also can be housed, and this housing sealed to the wall of the glovebox. A motor housed in this way usually requires gas cooling or water cooling, and gases or vapors from the insulation or lubricant are liable to adulterate the box atmosphere.

Because of the disadvantages inherent in shaft seals and housed electric motors, a more satisfactory way to rotate a high-speed drive in a glovebox is to employ an oil-motor drive. Oil motors, similar to those used in aircraft, are small compared to electric motors of comparable power. They lend themselves to speed control over a wide range and permit easy reversal. A rotating seal is replaced with high-pressure oil lines passing through dependable static compression seals in the glovebox wall.

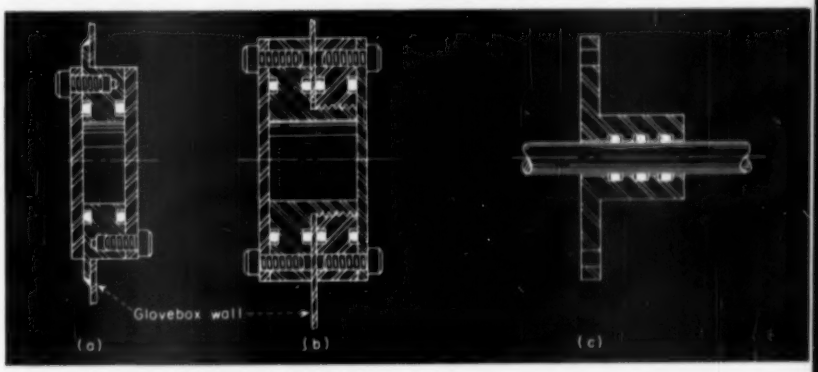


**FIG. 3. Openings permitting safe entry and extension of contaminated gloveboxes. In (a) grooved plate to receive O-rings is welded to sheet-metal wall; in (b) it is O-ring gasketed to wall. As long as inside cover plate remains sealed, any fitting can be gasketed to outside flange. If flanged opening is big enough, gloveboxes can be attached to extend system. Closed-end furnace tubes have been attached to glovebox by means of a water-cooled flange—access is had to furnace from inside glovebox without problem of dissipating radiant heat of furnace were it inside box.**

**Seal in (c) permits passing cylindrical object into system through O-ring seals while maintaining system tightness. This procedure cannot be reversed without contaminating room. If inert atmosphere must be protected, gas trapped between items introduced must be minimized. Seal can also transmit reciprocal motion; flexible boot around external portion of seal, attached to glove-box wall and reciprocating shaft, should contain contaminated part of shaft**

## Details of Construction

Because of their different requirements, the Research Laboratory and Fuel Fabrication Facility glovebox systems differ in structural details.

**Research Laboratory.** The Research Laboratory glovebox system is composed of welded 14-gage type 304 stainless-steel-sheet boxes connected together with O-ring seals wherever possible. To permit flexibility, the boxes are not welded together. The ends of the boxes were deep drawn with ¾-in. radii at edges and corners. The side walls were also formed with matching radii. The assembly was fusion welded and the weld surfaces inside the box were ground smooth. The box contains no inaccessible sharp corners or crevices for accumulation of fine particles, and the interior surfaces are smooth and easy to keep clean.

Window, door, and glove-port-cover construction are shown in Figs. 4–6. This gasket design has sealed the system for 1½ years without attention.

**Fuel fabrication facility.** Gloveboxes for the fabrication facility are extruded-aluminum-alloy frames with inset clear-plastic window. Extruded

shapes are shown in Fig. 7. A prototype assembly is shown in Fig. 2.

The 618-T6 aluminum alloy, chosen for its hardness and resistance to nicks and wear, has some drawbacks for welding. It tends to soften immediately adjacent to the welds, but since it remains hard elsewhere, this was not considered objectionable. It is weldable but is somewhat subject to shrink cracking at temperatures near its welding point. Shrinkage cracks were eliminated using No. 43 filler rod, which melts at a considerably lower temperature than the 618; by using inert-gas-shielded alternating-current tungsten arc welding to minimize the heating zone; by heating the extrusions and castings before welding; by insulating the parts from the welding fixture to prevent too rapid cooling; and by making full penetrating welds.

After welding the glovebox frames, the gasket and flange surfaces were carefully scraped or machined to remove any roughness or interfering weld beads. Care was exercised to maintain the original contours of the gasket grooves and to avoid gouging.

## The Glove Problem

Gloves are a vulnerable part of systems wherein radioactive and pyrophoric materials are handled—some consider them the weakest link.

The fact that gloves can be replaced with relative ease has placed the emphasis on improving glove-change techniques. However, even the best glove-change technique presents a potential hazard, especially where radioactive metal powders are handled. Realization of this has helped to renew interest in the glove quality. The longer gloves last, the less often they must be changed, and, therefore, the less chance of spreading contamination.

In addition to a desire for a better general-purpose glove, there is a need for improvement in special properties for certain applications, e.g., for protecting inert atmospheres (impermeability to moisture), for handling highly poisonous materials, bacteria, and viruses, and for sterile work areas.

## Standardization

Early glovebox workers specified glove forms and materials to satisfy their own requirements. But users and suppliers are finally cooperating in an effort to standardize specifications that are meaningful to performance and

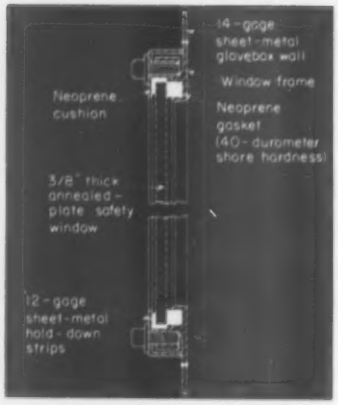


**FIG. 4. Window seal for Research Laboratory glovebox. Stainless-steel frame has welded mitered corners; rectangular groove was milled and hand dressed at corners. Lip on frame assures welding frame box with minimum warpage; some straightening after welding was necessary to have seating surfaces in flat plane. Continuous gaskets are thick enough to allow 30% compression before window is seated. Torque of 10–13 in.-lb on hold-down screws, 2¼ in. between centers, attains leaktightness without pressure being too localized at screws**

at the same time practical within the limits of the manufacturing process. There is now a concentrated effort to develop specifications for an arm-length glove for production or heavy usage where strength, long life, and shielding are desired even at the expense of "feel." A suggested glove is made of neoprene (by the milled process) and has an 8-in.-i.d. cuff, a 30–32-in. length, and a minimum 0.030-in. thickness (*2*).

It may be difficult to alter existing gloveboxes to accommodate the standard glove. For example our Research Laboratory now uses an 8⅝-in.-cuff glove. We note that stretching an 8-in.-cuff glove onto our glove port tends to shorten its life. Therefore, we will in any case continue to use an 8⅝-in.-cuff glove. Also, the proposed standard glove is not intended as a universal glove.

## Design Considerations

In designing gloves, one must consider the location of the glove ports, the geometry of the gloves, and the properties of the glove material. These must be adapted to the work being done.

Although we are aware of several independent design studies, little information is available in the literature. Two exceptions to this are the British (*3*) and University of Rochester (*4*) reports. Human engineering studies on a Rochester staff of 20 revealed that glove-port location and size was critical to working comfort and safety. In this case 9-in.-diameter ports were decided upon with 16–18 in. spacing, center to center, and with centers located 54 in. from the floor to permit work from a standing or sitting position.

The University of Rochester investigators decided that, for their operating conditions, the length of the glove should be greater than the longest reach of any operator—39–40 in. A study of hand proportions revealed that the length was less variable than the width and thickness. The glove hand had to be made to fit the largest operator's hand and the wrist large enough to pass the thickest and widest hand. Fingers were designed ¼ in. shorter than those of the average user to ensure sensitivity. Also, an ambidextrous thumb (projecting flat from the side of the palm) permitted use by the right or left hand.

In this study, thin flexible gloves were needed for a high degree of feel. Pure rubber gloves were unsuitable for the intended application because of absorption of and permeation by radon, poor strength, poor resistance to chemicals, and, in general, short life. The glove now being used is a specially compounded low-porosity neoprene, which permits dipping unusually thin films (0.006 in.) resulting in extreme sensitivity and flexibility.

The suitability of this glove for its intended application depends upon some features that preclude its use in plutonium-metallurgy glovebox work. The negative pressure in the gloveboxes tends to pull the gloves off of the hands, and the greater the glove length the more this is accentuated; 30–32-in.-long gloves are the maximum recommended at ANL, with some applications calling for shorter gloves. Also, greater thicknesses of neoprene are needed for shielding against beta and low-energy gamma radiation; the preferred thickness at ANL and other laboratories is 0.030 in. The greater thickness results in less flexibility, which discourages the use of the neutral thumb, and, in fact, makes desirable curved fingers on a full-fashioned hand.

As was the case in the University of Rochester study, early experience at most laboratories was with natural-rubber gloves. These are still used in many applications where the activity

level is low and where delicate operations require a sensitive touch. However, such gloves deteriorate rapidly.

**Neoprene.** At present neoprene is favored by most laboratories where high-intensity alpha-active materials are handled. The properties of neoprene depend upon its composition, which can vary widely, and the method of compounding. Although many of its basic characteristics are only equal to those of rubber, it is far superior in its stability under most conditions (*5*).

Unlike many synthetic rubberlike materials, neoprene lends itself to the manufacture of arm-length gloves by dipping processes. Both milled and latex processes are used. Milled neoprene can be compounded to develop the properties that appear to be most desirable for gloves. However, the milled process requires multiple dipping, which results in greater difficulty in controlling uniformity of thickness as well as defects in the dipped film. Gloves made by the latex process have, in general, somewhat lower properties, and are more permeable to moisture than those made by the milled process, but the film can be controlled within close tolerances (single-dip process). At ANL we favor the milled neoprene glove because of its better properties. However, there is little agreement among users, suppliers, and manufacturers as to what properties are important to glove performance—suitability is best determined by service tests.

**Butyl rubber.** Butyl rubber (*6*) has much lower moisture permeability than neoprene and many other synthetic elastomers (*7*). In general most of the properties of butyl rubber are desirable. However, its strength is low, it has a low modulus, and it is subject to cold flow. A satisfactory method of producing butyl rubber gloves has not been developed.

**Inspection and testing.** At present, glove inspection usually consists of visual examination. Air-pressure tests under water are sometimes used.

As a part of the development of standard gloves, much more rigid inspection and testing methods by the manufacturer are being considered. Material and glove dimensions will be specified carefully. Properties of interest include permeability, tensile strength, elongation at breaking, permanent set, hardness, and resistance to cutting, tearing, and abrasion. Of major concern is the retention of these properties in spite of aging, sunlight, ozone, heat, oils, and chemicals.

In addition, manufacturing defects to be looked for include patches, blisters, pin holes, cracks, protuberances, indentations, surface breaks, and embedded foreign particles. A proof voltage and leakage current test, modified after the standard electrical test for rubber insulating gloves contained in ASTM Specification D120-52T, should detect these defects (*2*).

## Working with Gloves

Gloves are changed at most installations when they become defective or when contamination is found on the outside of the gloves or glove flanges. However, the number of glove changes should be minimized because the procedure is potentially hazardous. Also, a sound used glove is a better risk than is a new glove—the new glove may have an undetected defect or may develop one early in its use. In general, neoprene gloves that are used continuously last longer (some as long as four years) than those that are used intermittently.

**Glove-changing techniques.** Glove-port design must permit changing gloves while minimizing the chance of releasing contamination to the room. One method (*3*) utilizes a cylindrical glove port and a glove mounted in a circular glove ring with a felt washer. This permits a new glove to be slid into the glove port forcing the glove and glove ring of the old contaminated glove into the box. This method is effective on large glove boxes but is somewhat cumbersome for small boxes.

Several variations of a double-clamp technique are used in this country to permit changing gloves without opening the box to the laboratory. Most of these use a flat metal clamp on the outside of the glove port and an expanding flat metal clamp with a soft rubber liner on the inside of the port. Although most workers believe that contamination may be averted for more than one such glove change, one must expect some contamination to show up after several glove changes—particularly be-

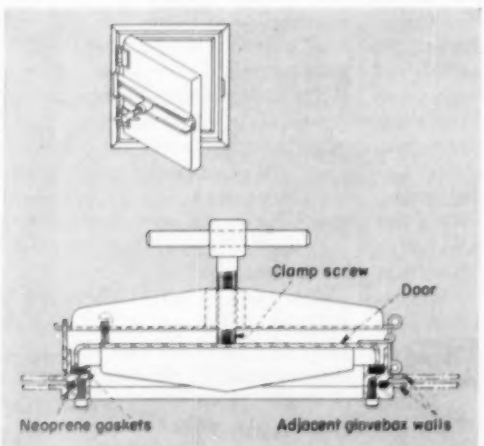


FIG. 5. Rectangular door is used between boxes or to isolate boxes from vacuum locks (Fig. 1). Circular doors are easier to seal, but space considerations precluded their use. Door shown is dished heavy sheet metal with stiffening ribs and is hung on floating hinges

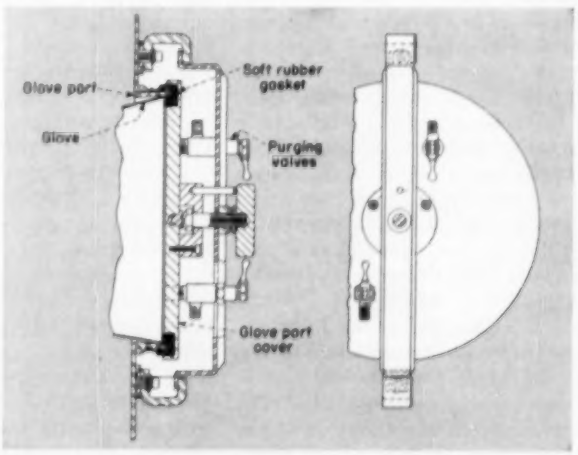


FIG. 6. Research Laboratory glove-port cover minimizes moisture and air diffusion into system through glove surface and is emergency cover in case of glove failure. An outside cover interfers with practice of tying gloves together outside box; inner cover does not interfere

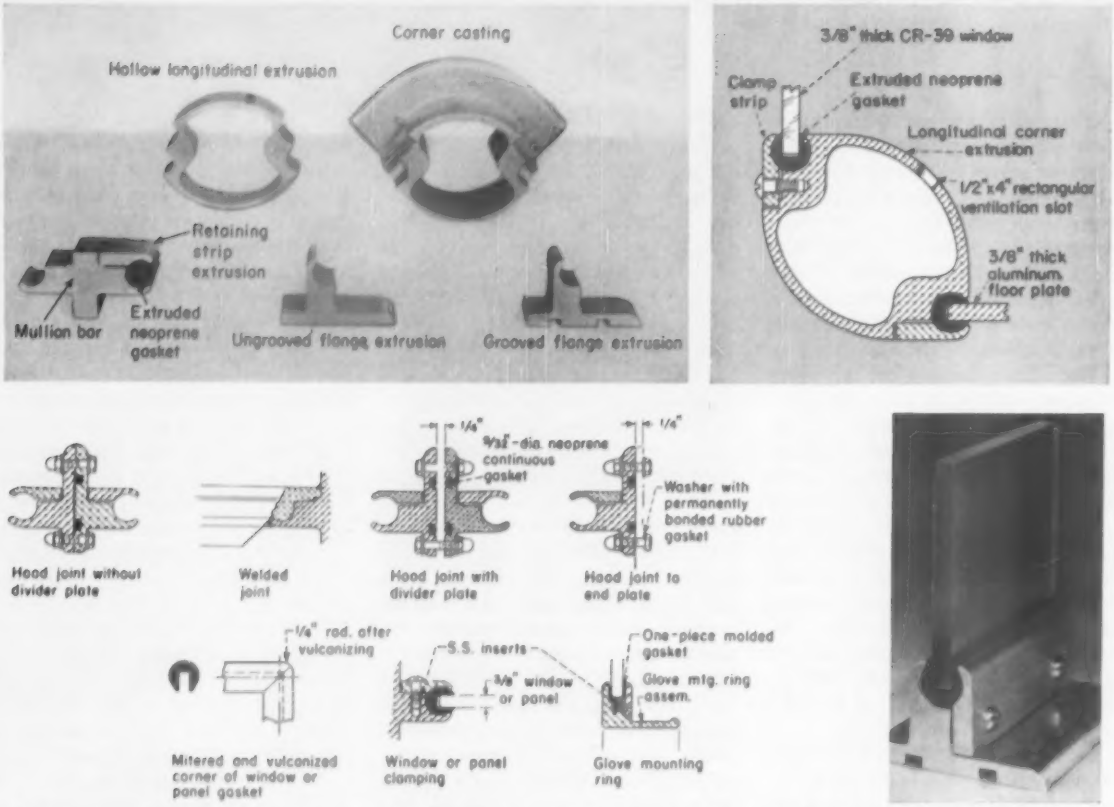


FIG. 7. As-extruded aluminum shapes for glovebox frames. (a) Cross section of extrusion for lower and upper longitudinal corner members; internal cavity running length of extrusion is distribution duct for air or inert-atmosphere ventilation; longitudinal recesses and channels at corners of extrusion allow installing cylindrical window gaskets and extruded retaining strips. Mullion-bar extrusion joins two $\frac{3}{8}$-in. window panels in double-module box or frames top windows and service panels; reinforcing rib down inner surface provides flange for attaching structures within box. Flange extrusions form bolting flanges at ends of double- and single-module box to allow attaching end plates or partitions and for interconnecting boxes. Corner casting (No. 43 casting alloy), for joining flange and longitudinal extrusions, has corner-gasket and retaining-strip grooves molded in place; it permits joining square-cut extrusions to form rectilinear structure. (b) Details of seals and gaskets for assembling members. (c) Retaining-strip extrusion applied to window gasket and to gasket grooves of frame extrusion. Gasket is also used for floor plates and service panels; cylindrical shape allows slight misalignment and distortion without leakage or localized gasket pressure

cause of plutonium-containing dust. Activity transfer by rubbing of contaminated against uncontaminated surfaces occurs in spite of a negative pressure to prevent gas-borne transport. Therefore, special precautions are taken to catch or contain the contamination on every glove change, and suitable face masks protect against inhalation.

In the Research Laboratory, we use an adaptation of the double-clamp technique, and, in over a year and a half of operation, have yet to experience even a slight count on the outside of glove ports. See Fig. 8.

An important part of our technique is the proper use of grease in the sealing area. We have used a low-vapor-pressure grease, such as Apiezon or silicone types, which obviously must not attack the neoprene. A thin coat of grease is applied to both sides of the glove in the sealing area. It helps to obtain a gas-tight seal with minimum pressure from the metal clamp ring, prevents friction folds in the glove during the clamping process, and minimizes friction between the glove and the metal port. Grease on the neoprene O-ring facilitates stretching the tight-fitting ring onto the glove port. We also feel that the grease on the gloves and O-ring improve their resistance to ozone attack. Finally plutonium-bearing dust tends to adhere to grease-covered surfaces, thereby fixing the contamination.

Early in our experience, while our glovebox system was still "cold" with respect to alpha activity, we found that minute pinholes developed in a localized ring where the gloves turn the corner of the glove-port flange. These holes were not always detectable with the unaided eye but were easy to find with a mass spectrometer helium leak detector. They developed in gloves that were used only sparingly and sometimes not at all so that the cause did not appear to be related to stretching during use. Also, almost all gloves that failed in this manner did so in the first two weeks of use. Otherwise they usually lasted indefinitely. Some leaks appeared to be associated with very small but sharp-edged surface imperfections on certain glove ports. Also, we found numerous hard foreign particles imbedded in the neoprene. Finally, other glovebox users suggested that the above potential sources of trouble are accentuated by our practice of stretching an 8-in.-cuff-diameter glove over the $8\frac{7}{8}$-in. maximum diameter of our glove port.

The pinholes were minimized by changing to an $8\frac{5}{8}$-in.-cuff-diameter glove to minimize stretch while avoiding wrinkling, by polishing the ports to eliminate sharp edges, and by impressing the manufacturers with the need for improved quality.

An expanding metal clamp band to seal the glove to the inside of the glove port is used on many glovebox systems, especially where alpha-active metal

powders are encountered. It has two purposes—to prevent strain and to permit glove changes without spreading contamination into the room. It serves the same function as the O-ring in Fig. 8. Some workers have objected to inner clamp bands on the basis of cost, interference with arm motion, and general nuisance. Nevertheless, it is standard equipment in most plutonium-handling installations. Inner clamp bands cannot be used to make a tight seal against the inside of the glove-port flange if the glove fits without stretching over the outside of the port flange as is our practice at ANL. The fact that the inside diameter of the flange is smaller than the glove diameter would lead to folds. A way out of this would be a glove that tapers at the cuff.

Thin-latex surgeons' gloves are worn as a secondary protection against contamination or spread of contamination in the event of a cut or torn neoprene glove and as an aid in monitoring for glove failures. It is standard practice at ANL to monitor the surgeons' gloves for alpha activity every time the hands are removed from the neoprene gloves.

Glovebox systems for handling plutonium are kept under negative pressure—limited to about 1½ in. of water because of the tendency for the gloves to stand away from the hands, thereby interfering with the sense of touch. Particularly in the case of long gloves, one tends to "lose" the glove when working with hands close to the ports. A helpful technique is to mount the glove rotated in the port. Then, on inserting the hand, one must twist the glove back to the natural position, which causes it to tighten around the wrist. This problem has also been solved by accordion-bellows-sleeve gloves and springs or rubber bands to retract the gloves. The greater surface of such gloves increases the possibility of defects and dust tends to collect in the folds.

**Precautions.** Where sharp objects must be handled, auxiliary holding devices often can protect the gloves, e.g., soft-leather protector gloves to fit over the rubber gloves and asbestos mittens to protect them against hot objects. Clamping arrangements to prevent glove movement while not in use are especially important in systems wherein less than atmospheric pressure is maintained. Gloves tend to be sucked into the boxes and fluctuations in pressure make the gloves "breath." A standard practice is to pull them out of the box and to tie them together. This precludes external glove-port covers; internal covers can be used (*8*).

Perspiration is objectionable where inert atmospheres are used because of the increased diffusion of moisture through the gloves and is uncomfortable. Cotton inner gloves have been tried, but become sodden in a short while. Antiperspirants in some cases cause serious skin irritations. Ventilated gloves (*8*) are cumbersome and expensive.


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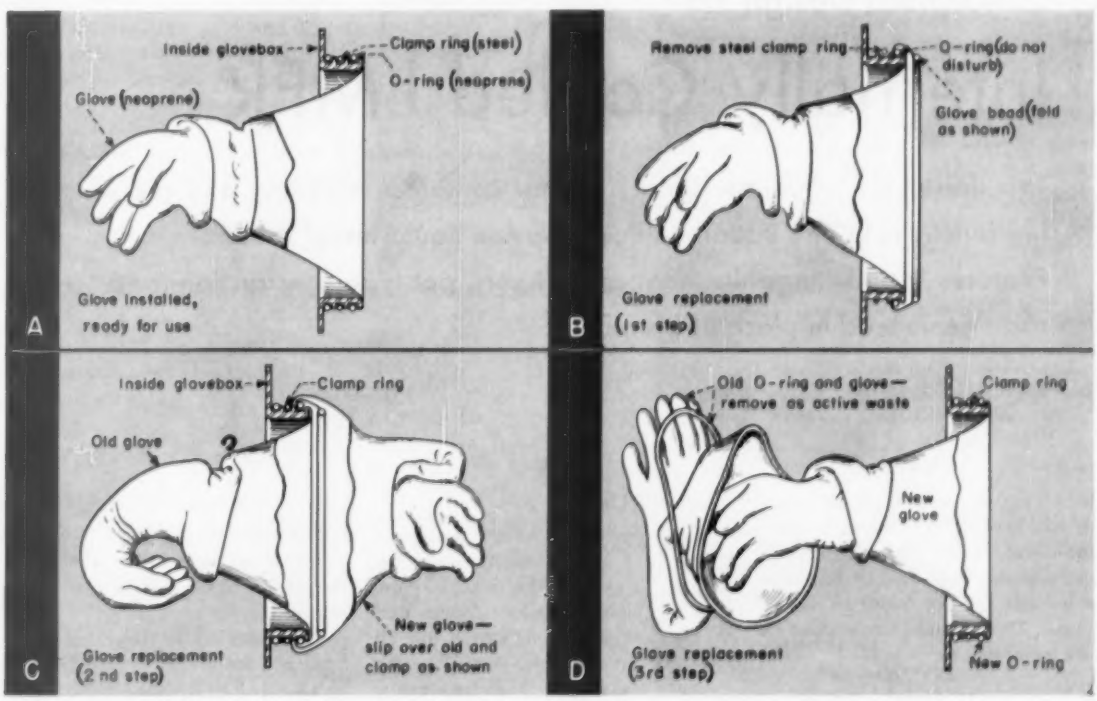


FIG. 8. Research Laboratory glove replacement procedure. Metal clamp ring has dovetail joint and is tightened with screw connection to give gastight seal. Glove is stretched only enough to prevent folding at seal. O-ring is temporary seal during glove change. Before changing, dust is removed from inside of port by wiping and sometimes by using small vacuum cleaners.

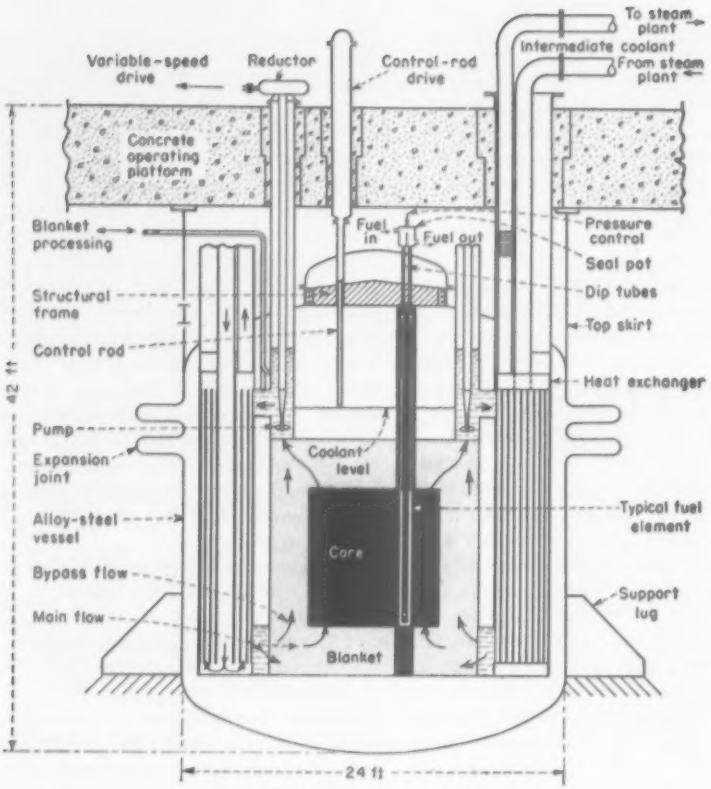


FIG. 1. Side view of the internally cooled liquid-metal-fuel reactor (LMFR) that combines breeder and coolant functions in one stream. For fuel-element design, see reference (1)

*Conceptual Design for*

# Internally Cooled LMFR

**This design for a 500-Mw (heat) reactor combines breeding and cooling functions in one intermetallic-dispersion liquid-metal stream. Features include graphite heat exchangers, pot-type construction, and radiogenic lead in place of bismuth**

By ROBERT J. TEITEL
*Brookhaven National Laboratory* Upton, N. Y.*

A CONCEPTUAL DESIGN for an internally cooled, $Th^{232}$-$U^{233}$ power breeder, liquid-metal-fuel thermal reactor is presented here. The design combines breeder and coolant functions in one stream. This is but one variant of liquid-metal-fuel reactors (*1*).†

* PRESENT ADDRESS: Dow Chemical Co., Midland, Michigan.

† Reference (*1*) is a series of articles on LMFR's that provide useful background for this article.

## Over-All Design

The arrangement of the reactor is shown in Fig. 1. Design conditions are in Table 1. The reactor core, breeding blanket, coolant pumps and intermediate heat exchangers are all installed in a single 24-ft-diameter pressure vessel. The pressure vessel is filled with graphite blocks machined and located to provide passageways for flow of fuel and coolant and wells for pumps and heat exchangers. The pumps and heat exchangers are removable through ports in the vessel cover; the reactor core might be removed and replaced in the same way.

The vessel is alloy steel; the bottom head and lower shell course are 2–2½ in. thick. The hydrostatic pressure of 30 ft of coolant amounts to 150 psi.

The vessel is supported conventionally at top and bottom to limit thermal-

expansion movement of the heads to the amount by which the graphite will expand, thus preventing looseness caused by the expansion of the steel away from the graphite at high temperatures. Expansion joints allow normal longitudinal expansion of the wall.

To prevent radial looseness of the graphite structure upon heating, a series of graphite blocks are pinned together to form constraining hoops.

Vertical propeller-type pumps lift the coolant from the top blanket and boost the head of liquid sufficiently to cause flow downward through the adjacent heat exchanger and upward through the inlet blanket, reactor core, and top blanket, thus completing the circuit. Slow-speed propeller pumps should be suitable for this low-head, high-capacity service. However, mixed-flow or even centrifugal pumps could be used.

The zone between the outside of the blanket and the inside of the containing vessel (Fig. 1) is filled with graphite blocks, except for eight vertical wells for secondary heat exchangers. The top of each vertical well is connected to the pump discharge by a suitable passageway. The bottom is likewise connected to the bottom blanket.

## Heat Transfer

The heat exchangers are single pass on both sides. Cool intermediate coolant goes up through the exchanger tubes and out to the steam plant. The core coolant (fertile dispersion) discharged by each pump flows downward through the exchanger well so as to give up its heat to the intermediate coolant. Double-wall exchanger tubes can be used as added safety measure.

The core consists of an 8¼-ft-diameter array of 1,350 impervious-grade-graphite fuel elements. These elements (shown in Fig. 3, p. 13 of reference *1*), each 2.25 in. o.d., stand vertically in a triangular array spaced on 2.56-in. centers. The coolant flows around each element and through a center channel.

The element has four principal sections; from the bottom up, they are

1. 2½ ft of solid graphite for the inlet blanket
2. 8¼ ft of tubular construction for the reactor core
3. 2½ ft for the outlet blanket
4. 8½ ft of fuel-feed section.

The principal differences between the various sections arise from the different nuclear and heat-transfer requirements. The bottom section is solid to provide atomic ratios of graphite and fertile solution for effective breeding and to permit full coolant flow. The core section must contain the proper atomic ratios of fuel, graphite, and coolant as well as proper disposition of heat-transfer surface. The outlet blanket zone must play the same part as the inlet section, with the addition of the necessary fuel-feed slots. The top section is necessary only for fuel feed and is arranged to fill the volume as completely as possible with graphite.

The 2½-ft breeding zone at inlet and outlet of the core is matched by a 2½-ft-thick side breeding zone of graphite blocks. These blocks are so machined as to permit residence and flow of a sufficient amount of fertile coolant to cause effective breeding and proper cooling to take place in this region.

Since leakfree graphite-to-metal seals are not available, a dip-tube system was devised to permit introduction and withdrawal of fuel. Each fuel element is essentially a U-shaped tube open on both legs at the top. Dipping into the liquid fuel in the top of each leg of the fuel element is a metallic dip tube that passes through the head of the vessel. The upper end of each dip tube is connected to the inlet (or outlet) half of the seal-pot arrangement outside the reactor. Gas pressure sufficient to elevate the fuel level into the seal pots is maintained inside the reactor vessel. Whenever fresh fuel enters the inlet side of a seal pot, a like quantity of spent fuel issues from the element into the outlet side of the seal pot. By this means, periodic or continuous renewal of the fuel charge can be achieved.

There is a dip tube for each element in the reactor. While this will complicate the fuel manifold, the advantage of being able to determine the performance of each element may be desirable.

The reactor was designed so that the entire heat load could be handled by six secondary heat exchangers. The remaining two would be stand by.

The liquid-metal film-heat-transfer coefficients were evaluated by Lyon-Martinelli equations (*4*). Typical calculations and assumptions are given by O. Dwyer (*1*). No "fouling" coefficients or factors of safety were included in the design calculations. However, they are believed to have been carried out with sufficient accuracy for the purposes of this evaluation.

In designing the core, it was neces-

**TABLE 1—Characteristics of Internally Cooled Liquid-Metal-Fuel Reactor**

| | | |
|---|---|---|
| Heat rate | | 500 Mw |
| Electrical power output | | 155 Mw |
| Fuel composition | $U^{233}$ | 0.700 wt. per cent |
| | Bi | 55.3 |
| | Pb | 37.1 |
| | Sn | 6.9 |
| Primary coolant composition | Th | 7.7 wt. per cent |
| | Bi | 92.3 |
| Core size, diameter and height | | 8.25 ft. |
| Blanket thickness | | 2.50 ft. |
| Steam conditions: | | |
| Top pressure | | 600 psia |
| Top temperature | | 800° F |
| Reheat temperature | | 700° F |
| Exhaust pressure | | 1.5 in. Hg |
| Total reactor holdups: | | |
| Bismuth | | 424 tons |
| Lead | | 6.5 tons |
| Tin | | 1.2 tons |
| Thorium | | 34.6 tons |
| U-233, core | | 64 kg |
| U-233, manifold | | 46 kg |
| Burnup time | | 220 days |
| Ratio, Mw heat/ton bismuth | | 1.18 |
| Specific power, kw/gm $U^{233}$* | | 4.50 |
| Breeding ratio (clean reactor) | | 1.17 |
| Doubling time* (clean reactor) | | 1,300 days (3.6 yr) |

* Based upon 110-kg U investment.

sary to compromise between nuclear and heat-transfer requirements, particularly since the primary coolant was also the breeding stream and the container that separated the fuel and coolant streams was also the moderator. For satisfactory nuclear conditions and for good fuel and primary-coolant compositions, the core had to contain certain volumes of graphite, fuel, and coolant. These volumes had to be arranged in such a geometry that the core did not become excessively large.

Ten different core geometries were investigated (*8*). The core design chosen represents a compromise between low holdup and ease of fabrication. The design conditions and calculated results for this particular core geometry are summarized in Table 2.

Sodium is used as an intermediate coolant between the reactor and the steam plant. Lead would have increased the total holdup of primary coolant by about 40 tons.

The design of the secondary heat exchangers is based on the production of 600-psi 800° F steam, capable of giving an over-all plant thermal efficiency of about 30%. By lowering the steam temperature, with consequent poorer plant efficiency, the holdup of primary coolant in the secondary heat exchangers can be reduced appreciably.

The heat exchangers are of conventional shell-and-tube design, without baffles, with the primary and secondary coolants flowing single-pass outside and inside the tubes respectively. The primary coolant flows, for the most part, in line between the tubes, minimizing the pressure drop across the exchangers for that stream. With the primary coolant outside the tubes, the heat exchangers can be suspended in long, vertical, cylindrical, graphite wells, exposing a minimum of welds to the primary coolant and permitting convenient replacement of the tube bundles. Countercurrent flow of the primary and secondary coolants, by introducing the cool secondary coolant at the bottom header of the secondary heat exchanger, leads to the smallest heat exchanger.

Table 3 gives the design and operating conditions for the eight secondary heat exchangers.

## Nuclear Calculations

The core size and the bismuth-to-carbon ratio were set by heat-transfer requirements. The $Th_3Bi_5$ concentration in the coolant was set by considerations of viscosity. With these limitations, calculations then were made to select the concentration of $U^{233}$ in the fuel that would make the core critical.

Fermi age theory was used. Reflector savings were first calculated using a two-group theory for a sphere having the same volume as the core cylinder and surrounded by a 2½-ft blanket of graphite and breeder slurry. By means of age theory, the U concentration in the fuel slurry then was varied to yield a critical cylinder having the dimensions of the reactor core augmented by the reflector savings (28 cm). The concentration of $U^{233}$ in the fuel thus obtained was 0.70 weight per cent, giving an over-all critical mass of 64 kg. Holdup in feed tubes raised the total fuel inventory to 110 kg. A reactor generating 500 Mw of heat would have an average core flux of $1.85 \times 10^{14}$ n/sec/cm².

The breeding ratio $g$ was then calculated from the formula

$$g = \frac{\Sigma_{Th}}{\Sigma_U}\left(\eta - \frac{1}{f}\right)R$$

where $\Sigma_{Th}$ and $\Sigma_U$ are the macroscopic thermal cross sections for Th and U, $\eta$ = number of neutrons produced per thermal neutron absorbed in fission in the core, $f$ = thermal-neutron utilization in U in the core, $R$ = blanket thermal nuclear efficiency.

We took $\eta$ as 2.33 and $R$ was computed as 0.90 from the composition of the breeder dispersion (7 atomic per cent Th), and 1.5% neutron leakage from the blanket. The latter was estimated from a two-group calculation. The two right-hand terms in the expression for $g$ yield 0.70 and 0.47 for the internal and external breeding ratios, respectively, or a total of 1.17 for a clean reactor. The calculations are summarized in Table 1.

A more realistic calculation of $g$ includes neutron losses to poisons. If, for example, Xe is not removed in the fuel processing operation and reaches an equilibrium concentration at the average flux mentioned above, $g$ will be reduced to 1.12 and the doubling time becomes 1,800 days (5 years).

This design has good nuclear efficiency as indicated by the high $g$, and high specific power. Both of these are requisites for an economical power breeder reactor.

## Discussion

No effort was made to optimize any one parameter of the design as might be required by an ultimate economic evaluation.

If it should become desirable to lower the Bi inventory because of its price or

**TABLE 2—Core Design**

| | | |
|---|---|---|
| **Design Conditions** | | |
| Total heat load | | 500 Mw |
| Top temperature of primary coolant | | 520° C |
| Bottom temperature of primary coolant | | 350° C |
| Core shape, right cylinder with height equal to diameter. | | |
| Ratio, fuel volume/coolant volume | | 0.200 |
| Ratio, graphite volume/coolant volume | | 1.46 |
| Cross-sectional area of each fuel channel | | 0.105 in.² |
| Reynolds number of fuel | | 6,000 |
| Maximum temperature of fuel | | 800° C |
| **Calculated Results** | | |
| Core diameter and height | | 8¼ ft |
| Number of fuel elements | | 1,350 |
| Number of fuel channels | | 5,400 |
| Linear velocity of fuel | | 0.223 ft/sec |
| Linear velocity of inside coolant | max | 9.85 ft/sec |
| | min | 3.80 ft/sec |
| | avg | 6.60 ft/sec |
| Linear velocity of outside coolant | max | 3.95 ft/sec |
| | min | 1.52 ft/sec |
| | avg | 2.65 ft/sec |
| Minimum temperature of fuel | | 442° C |
| Maximum gradient in graphite | | 1,000° F/in. |
| Minimum temperature of graphite | | 380° C |
| Total weight of fuel in core | | 10.0 tons |
| Total weight of coolant in core | | 50.9 tons |

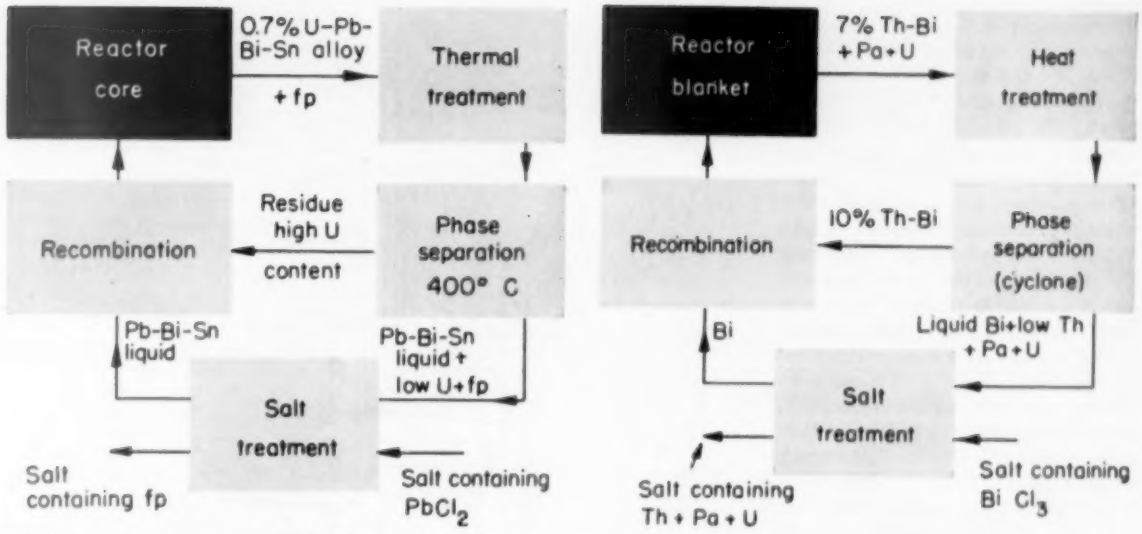


FIG. 2 Flow sheet for processing fuel (left) and blanket (right)

scarcity, there are several modifications that could be made. For example, Pb could be substituted for some of the Bi in the liquid phase of the fertile coolant dispersion. The fact that the Bi inventory *can* be reduced is one of the features of this reactor design.

To increase the reactor's specific power, the U inventory should be lowered. This can be done by improving the core heat-exchanger design to reduce the critical mass and by decreasing fuel holdup in the header system. If ten fuel rods were grouped together with one set of header tubes in the current design, the inventory in the header system would be reduced from 46 to 4.6 kg and the specific power would be increased 60%.

Graphite technology plays an important role in the design of internally cooled reactors. The development of graphite heat exchangers is very important. This design has been shown to some graphite experts and they believe that what has been proposed in this reactor design can be fabricated.

**Dispersions.** The use of dispersions also presents a new problem. The movement of the dispersions is not of great concern, but if the movement ceases the particles are free to settle or float. Also, there is little experience with dispersions such as those used in this reactor design. Several features of the application of these dispersions in reactors are:

1. In the fuel system, the dispersion is dilute and passes through small channels. These channels can be spiraled instead of vertical as shown in this reactor design, thus hindering the settling tendency. If the particles settle and the reactor is started, hot spots will be produced in the settled particles causing the particles to disperse.

2. The breeder dispersion has a poorer solid-liquid density match and must pass through large and essentially straight channels to minimize pumping power requirements. On the other hand, the dispersion must be concentrated with particles that hinder settling. In these reactors with heat generated from $Po^{210}$, $Th^{228}$, and $Pa^{233}$ radioactivities as well as some $U^{233}$ fission in the particles, it is difficult to picture a quiet bath of dispersion. The same self-agitating feature is possible in the blanket system.

**TABLE 3—Design Data for Eight Secondary Heat Exchangers**

| | |
|---|---|
| Tube material | 5 Si "Croloy" |
| Tube thickness | 0.125 in. |
| Tube inside diameter | 0.500 in. |
| Tube spacing (triangular) | 0.250 in. |
| Coolant | Sodium |
| Temperature drop for primary coolant | 520–350° C |
| Temperature rise for sodium | 300–470° C |
| Length of each exchanger | 18 ft |
| Number of tubes in each exchanger | 1,420 |
| Diameter of each exchanger | 3.5 ft |
| Hold-up of primary coolant | 140 tons |
| Hold-up of sodium | 7.8 tons |

## Reactor Materials

For an economical reactor design, it is necessary to use cheap and abundant materials of construction. But these qualities keep changing; metals that were considered unavailable ten years ago are now common. Since these changes can not be predicted, we used materials requiring the least prediction as to availability or cost.

The reactor core is fabricated from $U^{238}$, $Th^{232}$, graphite (for moderation) and the liquid-metal components (Bi, Pb, and Sn). $U^{233}$ can be obtained from a converter reactor, one that burns $U^{235}$ and produces $U^{233}$. Conceivably, the reactor could start as a converter and later operate as a breeder.

Bismuth, Pb, and Sn of very high purity are currently available in fairly large quantities. Of these, probably Bi is in the most limited supply. The present Bi requirements can be reduced by further design study; several alternative designs using more Pb and less Bi might increase the power produced per pound of available Bi.

Natural Pb is both abundant and cheap. In addition, there is another naturally occurring source, radiogenic Pb, that has a different isotopic analysis from that of regular Pb. From

the reported isotopic analysis and isotopic thermal-neutron cross sections (Table 4), the thermal-neutron cross section of radiogenic Pb is half that of regular Pb. Radiogenic Pb occurs in natural U deposits. It is known that the AEC has 80 tons of this radiogenic Pb on hand and more is probably available from other larger sources. Unfortunately, the information concerning the availability of this interesting material is not readily obtained because of its proximity to U production figures.

The reactor vessel is fabricated from Cr-Mo steels. These steels have shown great promise with regard to both their corrosion resistance to Bi (*5*) and their superior fatigue properties. Moreover, these steels are widely used in steam boilers where thermal-stress conditions are similar to those expected in the reactor design.

## Fuel System

In internally cooled reactor designs, the fuel moves through a system of tubes with high surface-to-volume ratio to promote heat transfer. In this design, these channels are ~¼ in. in diameter. For safety, it would be necessary to require that the U be removed from the reactor under any conditions and that segregation of U be prevented to avoid hot spots or loss. Moreover, the concentration of U in the fuel stream must be an order of magnitude higher (~1 atomic %) than that used in the externally cooled reactor designs (*6*).

A solution of U in Bi would be most desirable from the standpoint of mobility and uniformity, but an accidental cooling of the fuel stream can cause a U-Bi compound to precipitate. Unfortunately the compound precipitates in platelets that can readily bridge and plug a ¼-in.-diameter channel. Judging from the solubility of U in Bi (*3*), a 1% U alloy would require fuel channels maintained above 550° C under any circumstances. Since the maximum reactor-coolant temperature, as set by the heat-exchanger-steel fatigue limitations, is 550° C; there is some uncertainty as to the safety of a solution-fuel system. This led to the consideration of a dispersion fuel that would be stable under all conditions.

Of the dispersions considered (*3*), that of $USn_3$ in Pb-Bi-Sn alloys is best (Table 5). The density of the solid is very close to that of the liquid and probably the slightest movement would cause the solids to remain dispersed.

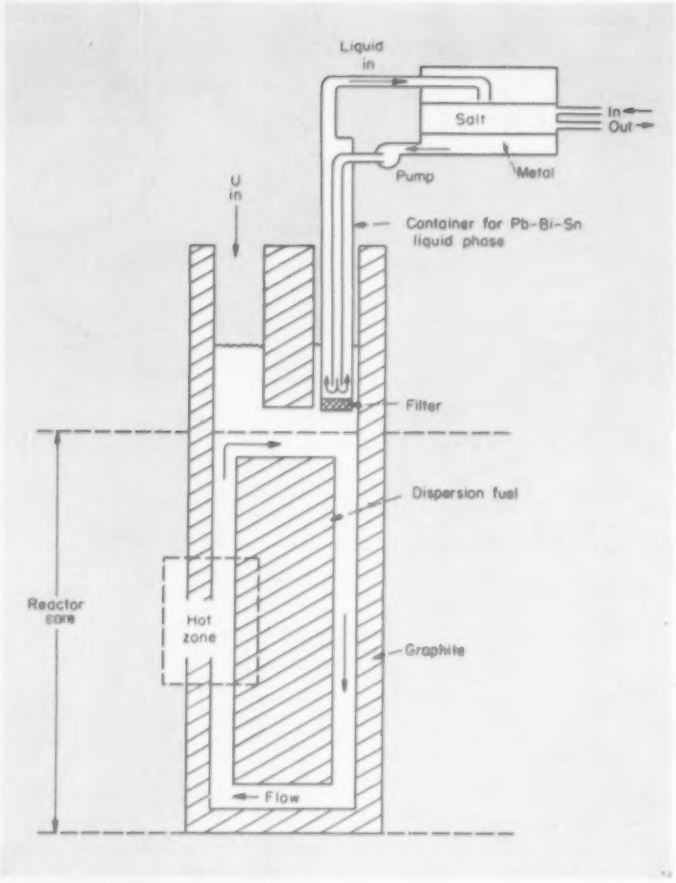


FIG. 3. Physical arrangement for processing fuel

When the dispersion is dissolved and reprecipitated, the compound appears in the form of 20–50-micron cubes. Thus, if the particle size changes due to radiation damage or growth, the size can be readjusted by completely dissolving the solids at high temperatures and reprecipitating the compound. There is a range of compositions for which these properties can be realized.

A dispersion containing 1.77 wt % $USn_3$ dispersed in a liquid containing 56.2% Bi, 6.0% Sn and 37.8% Pb is used as an example in this conceptual design.

## Breeder-Coolant System

Since the concentration of Th in the breeder system is necessarily beyond the solubility of Th in Bi, a dispersion of $Th_3Bi_5$ in Bi is used. The properties of this dispersion are shown in Table 5.

Unlike the $USn_3$ dispersion, the $Th_3Bi_5$ compound precipitates from solution in the form of platelets. These platelets are a metastable shape and upon sustained heating they thicken and tend toward a more equiaxed shape. Dispersions of equiaxed $Th_3Bi_5$ particles in Bi have been produced by reacting Th powder or chips with Bi at low temperatures. The platelet formation is avoided. This equiaxed shape can be maintained under all thermal conditions provided the dispersion is agitated and an appreciable quantity of compound is present. If the liquidus temperature (1,000° C for 7% Th-Bi) is exceeded, platelets are formed upon cooling. Several procedures for reconstituting the dispersion by a series of treatments are being studied. Results will be published later.

The particle growth at reactor temperatures during the periods between processing is not excessive and it is to be assumed that the dispersion will be reconstituted at these intervals.

The Th-Bi intermetallic compound has a higher density than the liquid

phase. However, the velocities expected in the conceptual reactor designs should be sufficient to keep the solids dispersed. Should the flow cease, the particles will settle in the channels. Settling will occur slowly, and there should be sufficient time to actuate standby equipment. Also, the reactor could be so designed that the Th would fill the core, thus reducing any danger of supercriticality.

This conceptual reactor design uses a 7.7% Th-Bi alloy that forms a dispersion having 19% solids.

## Chemical Processing

The proposed fuel dispersion could be processed by a fused-salt extraction (*1*). Another method (*3*) takes advantage of the low solubility of U in the Pb-Bi-Sn alloy; U is separated physically from the solids. The liquid phase is freed of fission products, without regard for the negligible quantity of uranium present. Fig. 2 is a flow sheet for the operation. The dispersed solids are dissolved in the liquid phase at a high temperature and are reformed by cooling. During this treatment the fission products trapped in the solid redistribute themselves into the liquid phase.

Experimental evaluation of this type of operation has been demonstrated using cerium tracers to represent the rare-earth fission products. Filtering a dispersion having approximately the composition of the one used in the reactor design, over 53% of the cerium passed with the separated liquid while 99.7% of the U remained in the residues. Chemical oxidation could be a simple way of purifying the liquid phase. The final step is to recombine the residue with the purified liquid phase and return the dispersion to the reactor.

A schematic physical arrangement for the processing of the fuel in the reactor without removal is illustrated in Fig. 3. A graphite fuel rod is machined with passages that complete a loop. By shading the cooling on one leg of the circuit, the dispersion can be moved by thermal convection. Moreover, the hot zone could be adjusted so that the temperature for the dissolution of the solid phase would be exceeded; thus incorporating the first step of the process in the fuel rod.

Phase separation is by a steel filter on the end of a tube dipped into a cool portion of the circuit. A tube concentric to the dip tube and placed above the filter circulates purified liquid phase above the filter. By applying a pressure differential across the filter, liquid phase can be removed and replaced by purified phase. The contaminated liquid phase is swept away to the purification operation, which is a salt contactor containing some low-melting salts having $PbCl_2$ as an oxidation agent. The fission products finally flow out with the salts; the U is confined essentially to the thermal-convection loop in the reactor core. Fresh U to replace that burnt would be added by another feed tube.

The proposed process for the breeder blanket dispersion would be similar to the later fuel process. Distribution ratios for the bred U relative to that of Th between the two phases have been demonstrated in the laboratory and appear feasible. A process flow sheet is shown in Fig. 2, right; it differs from that of the fuel only in that the dispersion might require an initial dilution step and the phase separation can then be accomplished by removing the liquid Bi by means of a centrifugal separator similar to a cyclone separator used for gases.

## Corrosion and Erosion

There are four places where corrosion or erosion are important:

1. Breeder dispersion against graphite.
2. Breeder dispersion against steel.
3. Fuel dispersion against graphite.
4. Fuel dispersion against steel.

Laboratory studies in the absence of radiation indicate that there will be no insurmountable problems from these sources.

As an example, in the fuel rod the interface between the graphite and the fuel dispersion will not exceed 650° C, according to calculations of O. Dwyer (*1*). Several experiments at temperatures above 650° C failed to show a serious carbide deposition. Thus, no trouble is expected from this.

* * *

*The author wishes to express his appreciation for the kind assistance of many of the members of the Nuclear Engineering Department at Brookhaven National Laboratory, in particular, O. E. Dwyer for his calculations on heat transfer, T. V. Sheehan and L. D. Stoughton for mechanical-engineering considerations, J. A. Fleck for nuclear calculations, and F. T. Miles for his help in the preparation of this article. Others who contributed indirectly are D. H. Gurinsky and J. S. Bryner.*

**TABLE 4—Macroscopic Cross Section of Radiogenic Pb**

| *Mass no.* | *Wt. fraction,* n* | *Thermal capture cross section, σ (barns)* | *nσ* |
|---|---|---|---|
| 204 | 0.000903 | 0.8 ± 0.6 | 0.0007 |
| 206 | 0.8865 | 0.026 | 0.0230 |
| 207 | 0.0833 | 0.7 | 0.0583 |
| 208 | 0.02926 | <0.001 | nil |
| Cross section for radiogenic lead | | | 0.0820 |
| Cross section for regular lead | | | 0.18 |

* Analyses performed by L. Kulp of the Lamont Geological Observatory (*4*).

**TABLE 5—Fuel and Breeder Dispersions**

| | *Solid phase* | | | *Liquid phase* | | |
|---|---|---|---|---|---|---|
| | *Composition (wt. %)* | *Density (gm/cm³)* | *Solubility (wt. %)* | *Composition (wt. %)* | *Density (gm/cm³)* | *Freezing point (°C)* |
| **Fuel** | 40 U–60 Sn | 10.0 | 0.005 at 350° C | 56.2 Bi, 37.8 Pb, 6.0 Sn | 10.0 | 215 |
| **Breeder** | 30 Th–70 Bi | 10.4 | 0.006 at 350° C | Bi | 9.8 | 273 |

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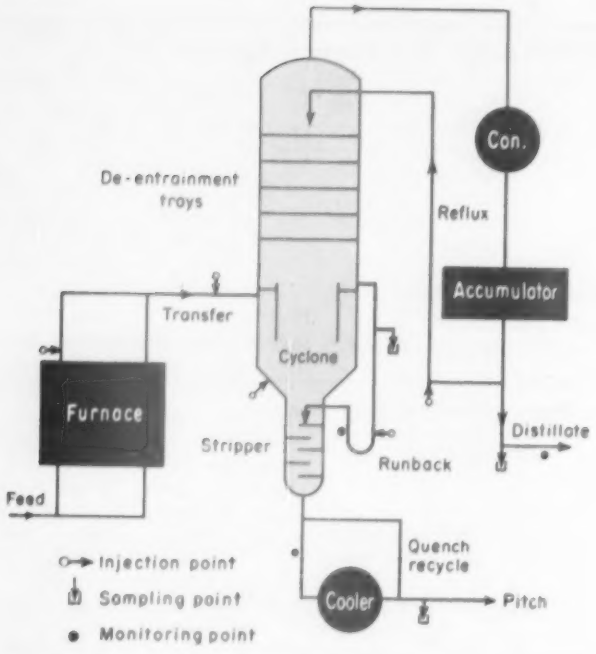


FIG. 1. Vacuum flasher unit operating at 54-mm pressure, 750° F, distillate flow of 480 liters/min, pitch-residue flow of 265 liters/min. Furnace heats and partly vaporizes feed in a series of hot tubes. More of volatile fraction vaporizes in large-diameter transfer line. Cyclone removes liquid phase (pitch). Tray section removes entrained liquid. Distillate reflux line recycles portion of distillate to top tray. Stripper is where steam removes more volatiles from pitch and carries vapor overhead. Runback line returns trapped entrained liquid from trays to stripper by gravity flow. Quench recycle stream of cooled pitch mixes with and cools pitch stream leaving stripper to prevent excessive cracking and coking

# Tracers Locate Entrainment

## Injection of $Ba^{140}$-$La^{140}$ into various points of a refinery vacuum distillation unit and measurement of activities downstream give data on location, mechanism, and magnitude of entrainment

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DISTILLING UNITS in refineries are designed to achieve the highest throughput consistent with obtaining a product of adequate quality. An important stage in petroleum refining is the separation by "vacuum-flashing" of the more volatile constituents of the residue remaining when the crude oil has been distilled at atmospheric pressure to recover gasoline and other products. This vacuum-flashed distillate is used as feed for catalytic cracking units. Of prime concern in distillate quality* is the degree of distillate contamination, which occurs by entrainment of nonvolatile feed constituents within the distilling unit. It is desirable to learn where entrainment occurs in the flasher so that changes in design can be made to improve quality, throughput, or both. Similar considerations apply to refinery distillations of other types.

Locating the source of entrainment is feasible only if a suitable nonvolatile tracer can be injected in any of several locations. When it is injected upstream of the entrainment zone, the tracer appears in the distillate; downstream, it does not.

Two general techniques are applicable: (a) injection of the tracer at a steady rate for a relatively long time, with analysis of distillate and residue streams in the steady state, (b) injection of the tracer rapidly, with determination of the total activity passing through the distillate and through the residue. Each method has advantages, which are listed on the next page.

Radioactive tracers are particularly useful in such an application because of the inherent sensitivity of detection. For example, gamma-emitting isotopes are measurable with accuracies of $\pm 10\%$ in 30 min in concentrations as low as 200 dpm/liter, or $10^{-4}$ $\mu$c/liter (*1*). Although refinery distillation units commonly have throughputs of the order of $10^5$ liter/hr, activities in the millicurie range spread over an hour's operation can be measured accurately. Moreover, this amount of activity can be contained in a small amount of chemical compound so that operation of the distilling unit is not affected by the introduction of tracer.

Another advantage of radioisotopes is the simplicity of detection and analy-

* On contact of such a distillate with cracking catalyst, any nonvolatile metal constituent is incorporated into the catalyst, and in many cases such contaminants have bad effects on the catalyst performance.

## What Kind of Tracer for Large-Scale Studies?

1. Half-life between 7 and 30 days. A shorter half-life imposes problems of scheduling, and the larger quantity necessary for the synthesis stage prior to the tests introduces a greater radiation hazard. A longer half-life imposes possible problems of lingering radioactivity in refinery equipment; this could require extraordinary precautions if an emergency shutdown occurs too soon after the test.

2. High probability of gamma emission per disintegration. Since analysis by detection of gamma rays is more convenient and sensitive (1) than that for beta particles, it is the gamma emission that is utilized, and beta emission merely poses an extra contamination problem. Thus, it is desirable that the gamma/beta ratio be high.

3. Energy of gamma photons >0.2 Mev. The efficiency of detection of low-energy gamma rays falls off rapidly as the energy decreases, and accurate calibration of monitoring arrangements becomes difficult.

4. Specific activity >0.1 mc/millimole. Since activities of the order of 100 mc are frequently used in a test series, the physical amount of isotopic compound becomes too large for facile handling in the synthesis stage if the specific activity is low.

5. The isotopic element must form a compound with certain necessary chemical and physical characteristics.

6. Any daughter radioisotope must exist in a chemical form that behaves chemically and physically like the isotopic compound used.

## Advantages of . . .

### . . . Slow, steady injections

- Fluctuations in unit operation are detected readily, and performance can be averaged.
- Phenomena such as adsorption of tracer are less likely to interfere.
- This method is more accurate since integration of long concentration "tails" is not necessary.
- Accurate time of sampling is not necessary.

### . . . Fast, pulse injections

- Extra data on flow rates, recycling, and mixing characteristics are obtained.
- The method is simpler to perform.

# In Distillation Units

sis. Oil samples can be counted by dipping a counter in the sample or by holding the counter against it. Much information can be obtained by mounting counters on pipelines of the distilling unit itself, and observing the fluctuations in activity. These counters can be calibrated to register the instantaneous specific activity of the flowing liquid.

## Choice of Tracer

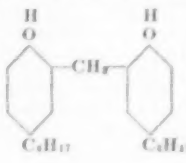
For large-scale studies of this type certain characteristics are essential. These properties are listed above. Of isotopes available, the $Ba^{140}$-$La^{140}$ fission product meets the criteria most favorably. It is available from Oak Ridge at nominal cost, and has a half-life of 12.8 days (40 hr for the $La^{140}$ daughter), and is carrier-free. The decay scheme is complex; on the average 3.46 gamma photons and 2.0 beta particles are emitted per $Ba^{140}$ disintegration (1.0 represents weak 30 kev photons).

For applications with crude oil "straight-run-residue" feed, where the isotope is to trace the nonvolatile constituents, the isotope must be present as a compound that is oil-soluble and nonvolatile, and the compound must be thermally stable (must not precipitate) at the temperatures encountered. Also, since the concentration of the isotopic compound in the distillate is quite low, it must not adsorb preferentially on the surfaces of the unit.

The barium salt of a high molecular weight phenol, "Amberol"* was chosen as a suitable compound. Tests demonstrated that the compound had negligible volatility and was sufficiently thermally stable. It is not known in what chemical form the $La^{140}$ daughter exists, but in all cases it remained with $Ba^{140}$.

Since the concentrations of active compound in the distillate are quite small (~0.1% of the injected material appears in the distillate), the possibility of selective adsorption of this compound on the condenser walls must be borne in mind. This is found to be particularly serious with certain surface-active compounds. The possibility of adsorption with the Amberol compound was checked in a separate experiment, performed in another distilling unit. Two samples of isotope with identical activity (0.1 mc), but widely different amounts (0.078 millimoles vs. 10 millimoles), were injected successively into the unit. Total activities passing a counter in the residue line were closely similar, indicating adsorption was not a problem in this particular system with an amount of isotopic compound of the order of 0.1 millimole. Adsorption might still present a problem in a system with condensers or coolers with a larger surface.

* This compound, obtained from Rohm and Haas, Co., has the structure




## Test Procedure

The technique was applied to the study of a refinery vacuum flasher unit shown in Fig. 1. During the tests, which required several days, the operation of the flasher was maintained at nearly constant conditions. The unit produced distillate containing approximately 0.4% of nonvolatile material.* The location within the unit at which

* As determined by analysis of pitch and distillate for trace metals.

**TABLE 1—Results of Entrainment Tests**

| Injection site | Total stream activities, (μc) | | | Fractional entrainment* | Activity injected, (μc) | Recovery (%) |
|---|---|---|---|---|---|---|
| | Distillate | Runback | Pitch | | | |
| Distillate reflux | 1140 | 913 | 1470 | 0.49† | ~3500‡ | ~80% |
| Furnace outlet | — | 266 | 6550 | 0.039 | 6000 | 110 |
| Transfer line (pulse) | — | 306 | 7220 | 0.041 | 5200 | 142 |
| Transfer line (cont.) | — | 376 | 11765 | 0.036 | 10200 | 119 |
| Cyclone closure | — | 362 | 4235 | § | 5000 | 85 |
| Runback line | — | 232 | 4530 | 0.049 | No determination | |

* Fractional entrainment is defined as the fraction of nonvolatile material carried overhead with vapor from a separation point under test.

† Injection is onto the top tray of the de-entrainment section, rather than into the feed or separator, as in the other tests.

‡ The vessel contained 7,000 μc, of which about half was injected, as shown by an essentially equal signal later when the vessel was flushed into the line.

§ Entrainment is positive but no quantitative figure can be assigned because nitrogen gas injected in this case with the isotopic material affected the flasher operation.

atomization or other forms of entrainment occur was sought as follows:

**1.** An injection of tracer was made into the top of the tray section to determine optimum times for distillate sampling and the extent of re-entrainment of distillate at this point.

**2.** Injections then were made successively at each of four positions—furnace outlet, transfer line, cyclone closure, and stripper—with analyses for activity in the distillate, runback, and pitch lines.

**3.** Finally, a continuous injection over a period of 75 minutes was made at the transfer line to provide accurate calibration data for the monitoring counters, to test the steadiness of operation of the flasher, and to provide accurate data on extent of entrainment.

Three pilot runs using smaller amounts of activity furnished information on the activity levels to be expected and the times of arrival at the monitoring and sampling points.

## Preparation of Tracer

Nonradioactive barium salt of Amberol was prepared by stirring 0.82 moles of hydrated barium hydroxide in aqueous solution with 0.82 moles of Amberol in toluene, for two hours at 80° C. The toluene phase contained the desired compound.

Inactive impurities and $La^{140}$ daughter* were removed from $Ba^{140}$ by adding carrier barium chloride to the acid solution of $Ba^{140}$-$La^{140}$ supplied, and precipitating the barium-$Ba^{140}$ chloride from a mixture of concentrated hydrochloric acid and ether. The purified salt was then taken up in water and allowed to exchange with the inactive barium salt of Amberol, by stirring the mixture for two hours at 80° C. The toluene phase then contained essentially all the activity.

A total of 63 mc of $Ba^{140}$ was thus incorporated into 24.5 millimoles of isotopic compound for the tests.† The toluene was removed and the material was dissolved in flasher pitch. This solvent was necessary since the material was to be injected in certain of the tests into vessels with contents at low pressure and high temperature; such conditions are likely to produce flash vaporization and resultant entrainment with solvents of significant volatility. The radioactive pitch was checked for homogeneity of activity and was then apportioned into the injection vessels. The homogeneity was further checked by comparing the radiation from each vessel with the weight of radioactive pitch in each.

## Injection Procedure

For pulse injections an empty large vessel was attached by a ½-in. gate valve to the top of the vessel containing the isotope (Fig. 2). This was filled with pitch containing ~50 gm of inactive barium salt of Amberol (this was to be injected along with the isotope, to reduce the specific activity of the compound and to minimize adsorption effect). In situations where entrance of a small amount of nitrogen gas would not upset flasher operation, a special cap was attached to permit application of a low nitrogen pressure to the contents of the large vessel. Completion of the injection was noted by sudden increase in nitrogen flow.

For injections in the transfer line it was considered essential to spread the injection over a period of at least one minute to average any fluctuations in behavior of this part of the system in

* The early removal of $La^{140}$ decreased the radiation level by about 80% during the preparation, and simplified the synthesis procedure.

† The tests were run about two weeks later. The growth of daughter activity (half-life 40 hours) during this period almost exactly compensated for the loss in activity by decay.

FIG. 2. Stainless-steel injection vessels were also shipping containers. Smaller—shown between the valves—were ⅝ in. i.d. × 12 in. long with pipe threads at each end plus threaded collars to accomodate caps. Larger vessels were 2¼ in. i.d. × 12 in. A 1½-in.-long tapered section ended in a short length of ½-in. stainless-steel pipe, threaded for attachment to a valve. Large end was threaded for a cap. Small vessels were used for pulse-type injections, large ones for continuous injections and flushing. At test site cap at one end of vessel was replaced by a ½-in. gate valve. A ⅜-in. copper tube connected gate valve with flasher. It passed through a packing gland and an open gate valve of flasher and was inserted so that material was injected at proper place in pipeline

which oil and vapor are moving at high velocity.

The assembled injection system was steam-traced with ⅛-in. copper tubing and insulated with glass wool. The contents were heated to ~200° F, and just prior to injection all valves except that below the injection vessel were opened. At the signal for injection the vessel valve was opened, allowing the contents to enter the pipe within a period of a few seconds. When the metering pump was used, the injection required about one minute for the "pulse" injection and 75 minutes in the "continuous" injection.

The method of injection used was satisfactory except in one respect. In certain instances, an air bubble was trapped in the gate valve at the base of the isotope vessel, and when the valve was heated and opened, the bubble was released, mixing the isotope with the flushing fluid above. A different type of valve would remedy this difficulty.

## Sampling and Analysis

On the injection signal, sampling of the pitch and distillate streams (and in the continuous injection, the runback stream) was begun. The runback stream could not be sampled in the pulse injections because the stream is very hot and running at low pressure and flow rate with only a gravity head. With the other streams in the pulse injections a rapid steady flow was established prior to the injection and was maintained at the same rate during the entire sampling period. Samples were collected in 5-gallon cans during the run. Sampling times were selected on the basis of the records of the pilot runs so that maximum information could be obtained. In the continuous run, 1-quart samples were collected at 10-minute intervals, care being taken to flush the sampling pipeline prior to sampling to ensure that the sample was representative of the material flowing at that time. The pitch samples in the 5-gallon cans were stirred while hot, and portions were transferred to 1-quart cans for counting.

After cooling to room temperature, samples were counted by two methods:

1. Distillate samples were counted by immersing a dip-type scintillation counter into a stainless steel beaker containing 1200 ml of distillate (*1*).*

2. Pitch and runback samples, because of their high cold viscosity, were counted "end-on" within the same shield by the same counter, by inverting the quart can containing the sample and resting the crystal end of the counter against the can bottom. Although the method is about one-third as sensitive as the "dip" method, the higher activity of these samples made the method easily applicable. The "dip" and "end-on" counting arrangements as applied to $Ba^{140}$-$La^{140}$ were calibrated against a standard solution.

## Monitoring

Since the runback line carries de-entrained pitch down to the stripper section, it provides a sensitive indication of entrainment from the cyclone. Interest in the source of entrainment primarily was connected with cyclone behavior; use of runback data is necessary to distinguish cyclone performance from that of the unit as a whole. It also affords a means of determination of entrained activity that is more reliable than examination of the distillate, in which the specific activity is much lower. Sampling the runback liquid would provide results of relatively high accuracy; however, for reasons given above the sampling difficulties are severe. Only in the run under steady-state conditions could meaningful results be obtained by sample analysis of the runback fluid.

To determine instantaneous specific activity levels, particularly in the runback line but also in other portions of the system, monitoring scintillation counters were employed. In each experiment, a maximum of four were used in positions shown in Fig. 1. The sites were carefully selected to provide high sensitivity and minimum interference by neighboring lines.

The counters were mounted so that their 1-in. sodium-iodide crystals were close to the pipe insulation with only a small air gap to prevent heat conduction to the counter. In nearly all cases the pipelines were standard 4-in. lines with 2–3 in. of magnesia lagging. Heat loss from the insulation was not sufficient to require stricter insulation precautions. Platforms were erected below the counters so that many lead bricks could be used for shielding.

Counters were oriented with respect to the pipe to give optimum shielding of the crystal. Shielding efficiency was determined from the counting rate resulting from exposure to a source held at the injection points and at the exit of pitch from the stripper. These counting rates, corrected for a 1 $\mu$c source, were <0.02% of those recorded by a solution of 1 $\mu$c/liter in the monitored pipe.

Power supplies and counter circuits were operated in the control room, about 80 feet from the flasher. The counter and all connectors were en-

## Flow Diagram

*If the volume flow rate of pitch from the stripper is* s, *and that of the quench-recycle stream is* q, *the flow rate at* P *is given by* q + s (*we assume constant temperature throughout; a similar expression could be defined on a weight basis*). *If the total activity leaving the stripper is* $A_s$, *the total count recorded in time* t *at* P *in the absence of the recycle stream would be* $N_s = V_c A_s/t$, *where* $V_c$ *is effective volume.*

*The total activity passing* P *and the flow rate are enhanced by the recycle stream, and the actual activity is* $A_p = A_s(q + s)/s$. *The total count recorded at* P *is given by* $N_p = V_c A_p/(q + s) = V_c A_s/s$. *Thus counters with equal effective volumes register the same number of total counts by the passage of activity in any part of such a recycle system, and calculation of* $A_s$ *using the* $N/V_c$ *values from a monitor at* P *or in the recycle stream merely requires using the appropriate flow rate.*

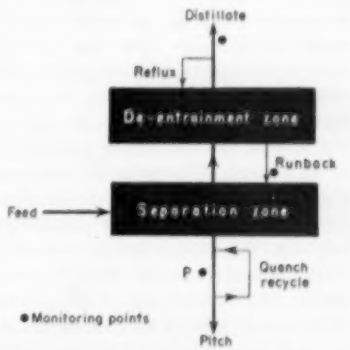



FIG. 3. Simplified flow diagram of vacuum flasher by means of which data from monitoring counters were evaluated

* The counter has a 1¾-in.-diam. × 2-in.-long sodium-iodide crystal, and a DuMont-6292 photomultiplier tube.

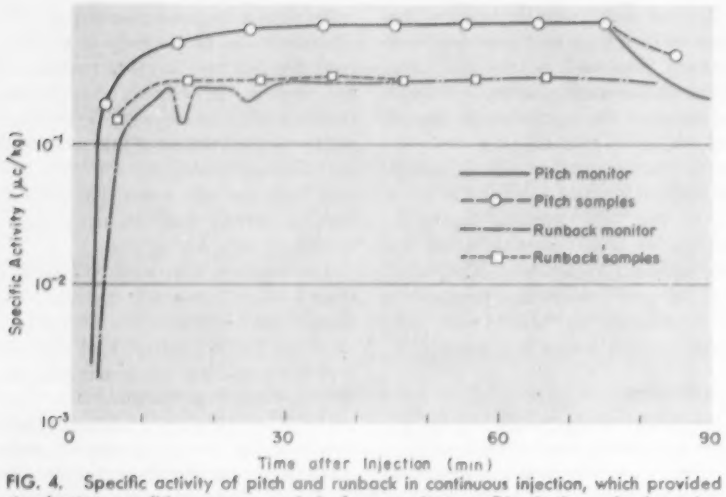



**FIG. 4. Specific activity of pitch and runback in continuous injection, which provided steady-state conditions over a period of many minutes. Dips in the runback monitor record are due to disturbances in runback flow from sampling. Sampling and monitoring specific activities agree since these data were used for monitor calibration**

closed in polyethylene bags with the wires emerging from the bottom so as to protect the system from moisture.

Since specific activity in the pitch could be determined accurately and is used as a standard to estimate concentrations of pitch in the other streams, and since specific activity in the runback fluid could be determined in the pulsed injections only by the monitoring counters, extra efforts were made to obtain quantitative information on these two streams from the monitoring counters. Output pulses from the ratemeter multivibrators were fed to scalers, and total counts were recorded for selected periods encompassing the specific-activity peaks.

This system was designed to obviate the serious difficulty previously experienced when pulses from the counter were fed to input circuits of both scaler and ratemeter. In such an arrangement slight differences in discrimination level of the two instruments result in significant differences in recorded counting rate. In spite of the improved arrangement the integrated ratemeter records did not agree exactly with the scaler counts for the same period. Differences up to 23% were experienced, with an average deviation of ±10.8%. On the average, the scaler counts were 95.5% of the integrated ratemeter counts for the same period. Some of the larger deviations could be accounted for by errors in establishing the scaler interval on the ratemeter record, and some error is possible in the integration procedure and calibration. In all cases below, the ratemeter calibrations were adjusted to correspond with scaler data.

In the operation of monitoring counters the ratemeters were first calibrated, and the counters were checked for optimum high voltage and background before the isotope was brought to the unit. With the isotope in place the new background was recorded for all counters. At the telephoned injection signal, the two scalers and all ratemeter recorders were started. Ratemeter scales were changed when necessary to maintain a signal of reasonable size. The scalers were stopped at times when the activity returned to a low value, as recorded by the ratemeters, but the ratemeter records were continued at slower chart speed until no further reduction in counting rate occurred. Background counting rates used for correction of the data to obtain net counting rates were the final equilibrium counting rates at the end of the experiment. The only exception was the steady-state run, in which a uniform decrease in background between the initial and final values was applied over the injection period. Over the course of the experimental program a gradual buildup of background to two or three times the initial value was noted; this was undoubtedly due to adsorption of isotope on the pipe wall.

## Stream Activities

Calculations of total activities in pipelines from monitor data are based on simple considerations. Total activity (dps) passing a counter equals total counts recorded times volume flow rate divided by "effective volume"—defined as an equivalent volume of solution in which radiation is detected with 100% efficiency.

The effective volumes are characteristic for each counting arrangement. These were calibrated *in situ* by observing counting rates recorded in the continuous injection, when specific activities of pitch and runback streams were virtually constant over a period of

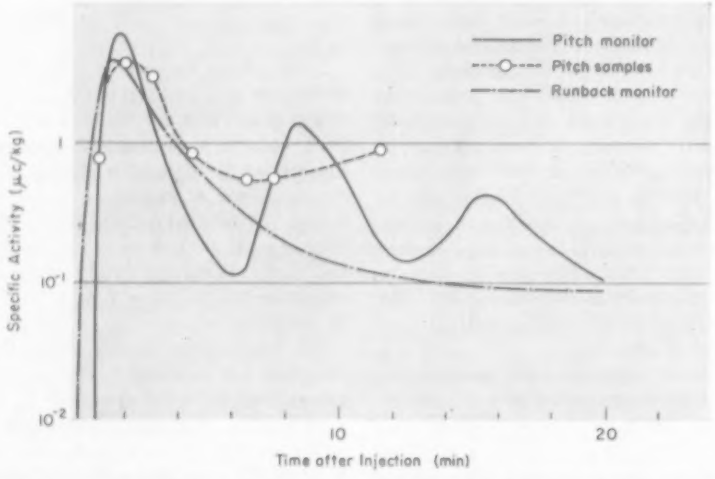



**FIG. 5. Specific activity of pitch and runback after cyclone closure injections. This is representative of data obtained in pulse injections into unit ahead of de-entrainment section. Recycle "echoes" are clearly evident, 6.8 min apart. This timing agrees with that calculated on basis of flow rates and pipe volumes. Entrained activity rises rapidly, then decays monotonically**

many minutes (Fig. 4). Actual specific activities were determined by sample analysis; the ratio of the cpm observed to the dpm/ml in the stream (the latter calculated using a density correction) gave directly the effective volumes of the monitoring counters for runback and pitch streams—4.72 and 2.11 ml, respectively. More complex calculations involving total counts and averaging over many minutes on the injection at the distillate reflux gave 5.45 ml for the counter at the distillate line. These values are about 60–70% of those obtained from simulated arrangements in the laboratory. The cause of the apparently reduced sensitivity in the refinery is not definitely known, but a relatively thin (⅛–¼ in.) deposit on the pipe wall could have this effect.

Corrected values for total counts recorded in a specified interval were determined in the following way. The scaling factors of the ratemeter records were corrected slightly by comparison with the more accurate scaler counts over a limited time period. The appropriate background counting rates were subtracted and net-counting-rate-vs.-time curves constructed. These exhibited exponential rates of decay as expected for a well-mixed system in which inactive material is added and mixed material is withdrawn. Effective residence times—defined as $t_e$ in the familiar exponential equation $I/I_0 = e^{-t/t_e}$—were found to be 27.8, 35.7, and 13.6 min for the pitch, runback, and distillate lines respectively. The total number of counts can be calculated by integration to infinite time. The remaining datum for the total activity calculation, the flow rate, is calculated from the refinery records, using a density correction to convert to volume flow rate at the monitoring point.

## Results

Values for total activities in each stream, calculated in the above manner, are given in Table 1. It is apparent from the relative activities in the last five tests that entrainment of radioactivity has occurred in each instance. Thus the major point of entrainment is downstream of the point at which the runback liquid returns to the stripper. It was concluded that turbulence in the stripper area together with flash vaporization of the volatiles in the runback liquid produce small droplets that are entrained in the current of steam and carried overhead.

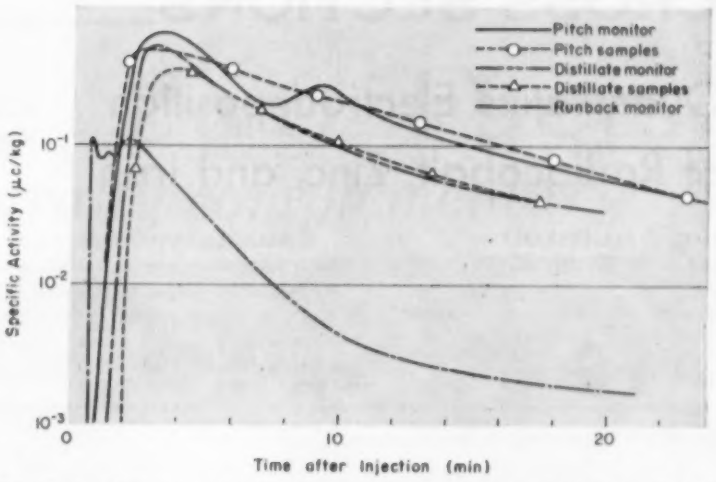



**FIG. 6. Specific activity of pitch, runback, and distillate after reflux injection. Part of the activity introduced onto the top de-entrainment tray is seen to appear almost immediately in the runback stream by some bypass mechanism with most of the remainder arriving over a minute later. A single small recycle echo is shown in pitch. Distillate monitor and sample curves superimpose well by definition since they were used to calibrate distillate counter**

With this as the basic conclusion, the data may be examined further to obtain values for the fractional entrainment at the stripper and for re-entrainment at the distillate reflux. For this purpose, the system may be viewed in the simplified form shown in Fig. 3.

In a simple branching system, in which the feed to the branches is thoroughly mixed, it is evident that the ratio of the activities passing through the branches is proportional to the flow rates of the labeled material in the branches. The runback stream returns essentially all of the pitch to the pitch line, except the small fraction carried on into the distillate and the fraction re-entrained. Ignoring the fraction carried to the distillate, and considering that all of the remainder finally passes through the pitch line, the fraction entrained in each cycle, $y$, is given by $(A_r/A_s) = y/(1 - y)$, where $A_r$ is runback-line activity. Values of $y$ thus calculated are given in Table 1. It is believed the high value for the cyclone closure injection is due to the disturbing influence of nitrogen gas injected after the pitch.

The injection into the distillate reflux line was designed to test the degree of re-entrainment of pitch from this stream. As shown in Fig. 3 the system involved injection into the recycle line; re-entrained fluid either passed on into the distillate or returned to recycle. If $z$ is the fraction re-entrained in each cycle and $a$ is the fraction recycled at the branch point, the activity passing into the distillate is given by $A_d = A_t[z(1 - a)/(1 - za)]$.

Since all of the activity not passing into the distillate ultimately passes through the pitch line, the total injected, $A_t = A_r + A_d$, is easily determined, and $a$ is known from the respective flow rates (corrected to the temperature at the branch point). Thus $z$ is 0.49. The data for the pitch counter is used in this calibration. Activity passing through the runback line should equal that passing the pitch, but in this experiment it appeared to be about 40% lower. The value in the pitch line is believed to be more accurate, since it was checked by sample analysis, and the runback flow rate in this experiment was believed to be seriously affected by the injection.

The performance of the flasher as a whole may be checked by observing directly the total activity in the distillate relative to that of the pitch. As expected, activity was detected in the distillate from all injections. This activity is too small to be monitored directly, and is too small in some cases to give reliable analysis of distillate samples. The specific activities of many of the distillate samples were as low as 50–300 dpm/liter at the time of measurement. These analyses corre-

*(Continued on p. 128)*

# CROSS SECTIONS

## Quantitative Electrodeposition of Radiocobalt, Zinc, and Iron

By C. J. MALETSKOS* and J. W. IRVINE, JR.†

*Massachusetts Institute of Technology*
*Cambridge, Massachusetts*

Quantitative electrodeposition of cobalt, zinc, and iron is a very useful technique for preparing counting samples for beta-ray and X-ray assay. Sources so prepared have a uniform surface density, are mechanically stable, and are ideally suited for handling on automatic sample changers. When properly stored, the sources can be used repeatedly for periods ranging from many months to years.

The procedures described here are relatively lengthy, but they are used in our laboratory on a mass-production basis so that the preparation time per sample is reasonable. One technician using a bank of 12 plating cells readily

* Radioactivity Center of the Department of Physics.
† Department of Chemistry and Laboratory for Nuclear Science.

**TABLE 1—Procedures for Electroplating**

| | *Co (a)** | *Co (b)* | *Zn* | *Fe*† |
|---|---|---|---|---|
| Solution composition | 1 ml $CoSO_4$ (10 mg Co/ml)<br>1 ml $Co^{60}$ tracer solution<br>20 ml conc. $NH_4OH$<br>10 ml 0.35*M* $(NH_4)_2SO_4$ | 1 ml $CoSO_4$ (10 mg Co/ml)<br>1 ml $Co^{60}$ tracer solution<br>25 ml 1*M* triethanolamine<br>5 ml sat. $(NH_4)_2SO_4$ | 1 ml $ZnSO_4$ (5 mg Zn/ml)<br>1 ml $Zn^{65}$ tracer solution<br>neutralize, then add<br>2 ml 10*M* NaOH<br>21 ml distilled $H_2O$ | 1 ml $Fe_2(SO_4)_3$ (10 mg Fe/ml)<br>1 ml $Fe^{55}$ or $Fe^{59}$ tracer solution<br>33 ml sat. $(NH_4)_2C_2O_4$<br>0.4 ml 3*M* $H_2SO_4$ |
| Current (amperes) | 1.0 | 1.0 | 0.85–0.90 | 0.85 |
| Voltage (volts) | 8–10 | 8–10 | 8–10 | 8–10 |
| Time (hr) | ~1.25 | ~3.5 | ~3.5 | ~2.25 |
| Initial *p*H | ~12 | ~8 | ~14 | ~4 |
| Final *p*H | ~8 | ~3.5 | ~10 | <7‡ |
| Initial solution color | deep pink | deep pink | colorless | yellowish-green |
| Time for colorless solution (hr) | ~0.75 | ~1–1.5 | | ~0.75 |

* Procedure requires hood to remove $NH_3$ fumes.
† The procedure described by Peacock *et al.* (*2*) has been modified for greater reliability. Halide ions, $SCN^-$, $PO_4^{=}$ and $Ca^{++}$, interfere with plating Fe and should be removed when samples other than standards are being prepared.
‡ After 1.5 hr of plating, solution tends to become basic. This must be prevented by dropwise addition of 3*M* $H_2SO_4$, maintaining *p*H at 6–7.

**TABLE 2—Test for Completeness of Electroplating***

| | *Co*† (3) *(in small test tube)* | *Zn*‡ (4) *(in small cylindrical glass-stoppered separatory funnel)* | *Fe*† (2) *(in small test tube)* |
|---|---|---|---|
| Solution composition | 1 ml plating solution<br>1 drop phenolphthalein soln.<br>Adjust *p*H with HAc and $NH_4OH$ until solution is just colorless<br>0.25 ml sat. $NH_4SCN$<br>0.5 ml *n*-amyl alcohol<br>Shake well | 1 ml plating solution<br>5 ml acetate buffer (1*M* NaAc + 1*M* HAc)<br>0.25 ml 0.1*M* $Na_2S_2O_4$<br>5 ml 0.01 gm/l dithizone§ in $CCl_4$<br>Shake well (relieve pressure with care) | 1 ml plating solution<br>2 drops 1*M* $NaHSO_3$<br>1 drop 10 gm/l $\alpha,\alpha'$-dipyridyl¶ (in 0.5*M* HCl)<br>Heat to boiling<br>1 drop 1.25*M* $Na_2S$<br>Shake well |
| Colors in 0–10 μg range: | | | |
| extractant phase | Pale yellow to pale green to green to blue-green | Pale green to blue-green to violet to pink | |
| aqueous phase | Colorless | Colorless | Light pink to red |

* Colors produced by test aliquots are visually compared with those of 0 and 1 μg standards prepared in same way and at same time as test samples. Color comparisons should be made as soon as possible since colors fade rapidly.
† Singly distilled $H_2O$ for preparing solutions and dichromate cleaning of glassware are satisfactory.
‡ Precautions for cleaning glassware and¶preparing solutions are given in references *4* and *5*. Singly distilled $H_2O$ is generally Zn-free.
§ Dithizone (diphenylthiocarbazone) solution (0.01 gm/l) is freshly prepared by diluting stock solution. Stock solution (0.1 gm/l) is prepared by dissolving dithizone (reagent grade, Eastman Co.) in $CCl_4$ (sulfur-free, No. 444, Eastman Co.) and is kept in tightly stoppered dark bottle at 10–12° C.
¶ The $\alpha,\alpha'$-dipyridyl should be kept in dark screw-cap bottle to reduce action of sunlight and air.

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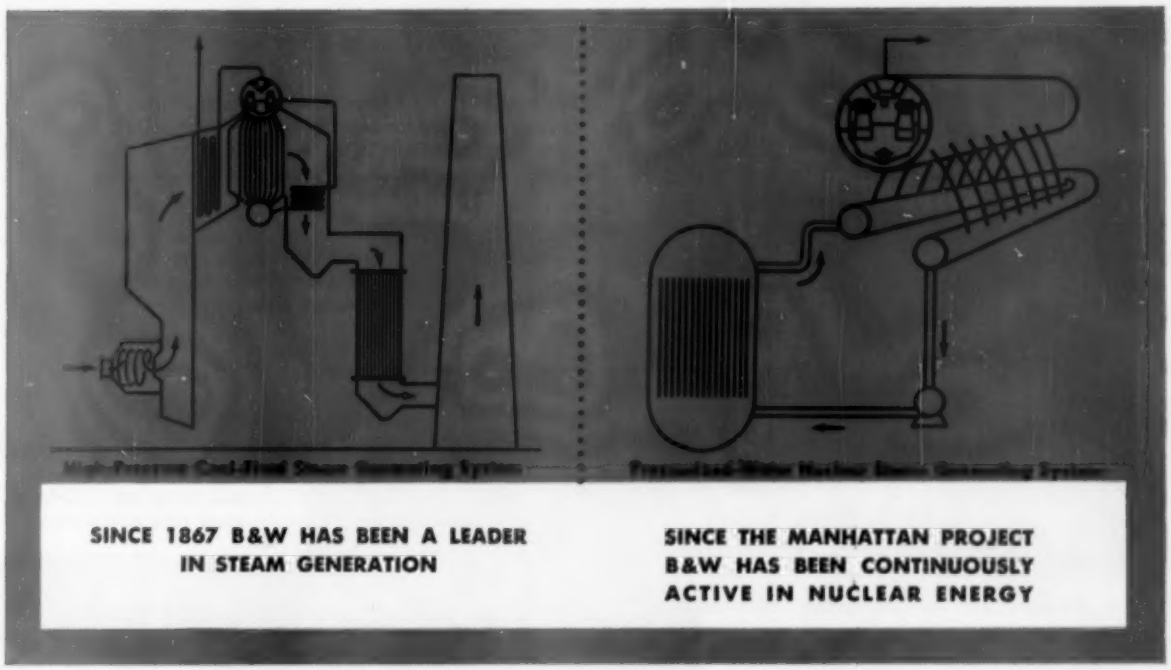

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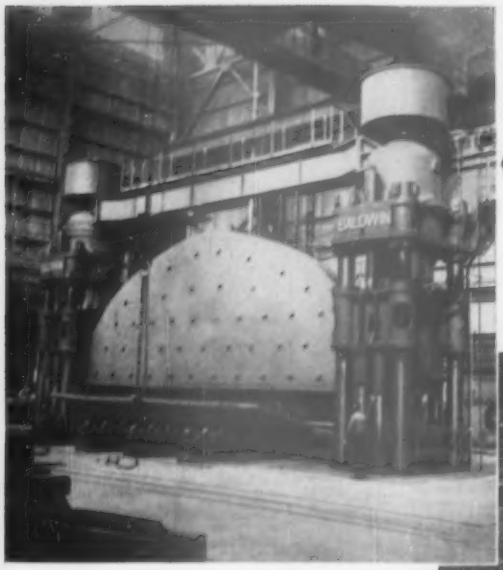

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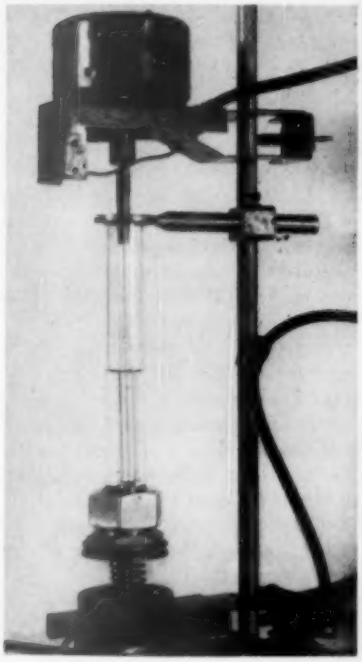

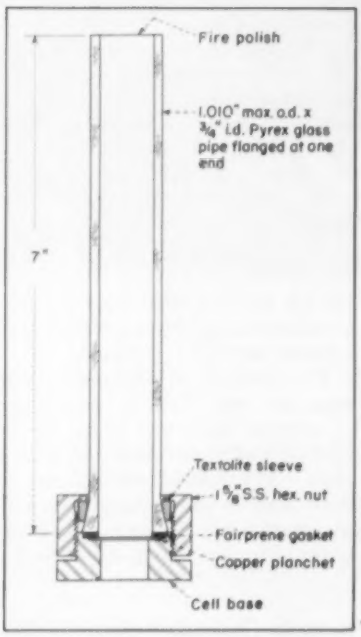


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## Procedures

Although there are numerous procedures in the literature (*1*) for the "quantitative" electrodeposition of cobalt, zinc, and iron, these are generally designed for 0.1–0.5 gm samples and do not remove the last 0.1–1 mg of metal from solution. To get consistent deposition of 5–10 mg of metal with better than 99% recovery, the solutions and plating conditions had to be modified extensively. The solution compositions and conditions for carrying out the electrodeposition are summarized in Table 1.

For samples of radioactive cobalt, zinc, or iron isolated from biological tissues, the amount of carrier added to the plating solution is adjusted so the final amount of metal is approximately that indicated in Table 1. Variations of 10% in this quantity cause variations in the self-absorption in the sample and consequently in the counting rate of only about 2%.

At the end of the designated plating time for each procedure, a 1-ml aliquot of the solution is removed to test for the completeness of deposition as described in Table 2.

If the test aliquot contains $<1$ $\mu$g of the element, operation is stopped and the cell is removed. The solution is quickly decanted and the cell and sample are rinsed with distilled $H_2O$. The sample is removed, rinsed again with distilled $H_2O$, and air-dried with a jet of clean dry air.

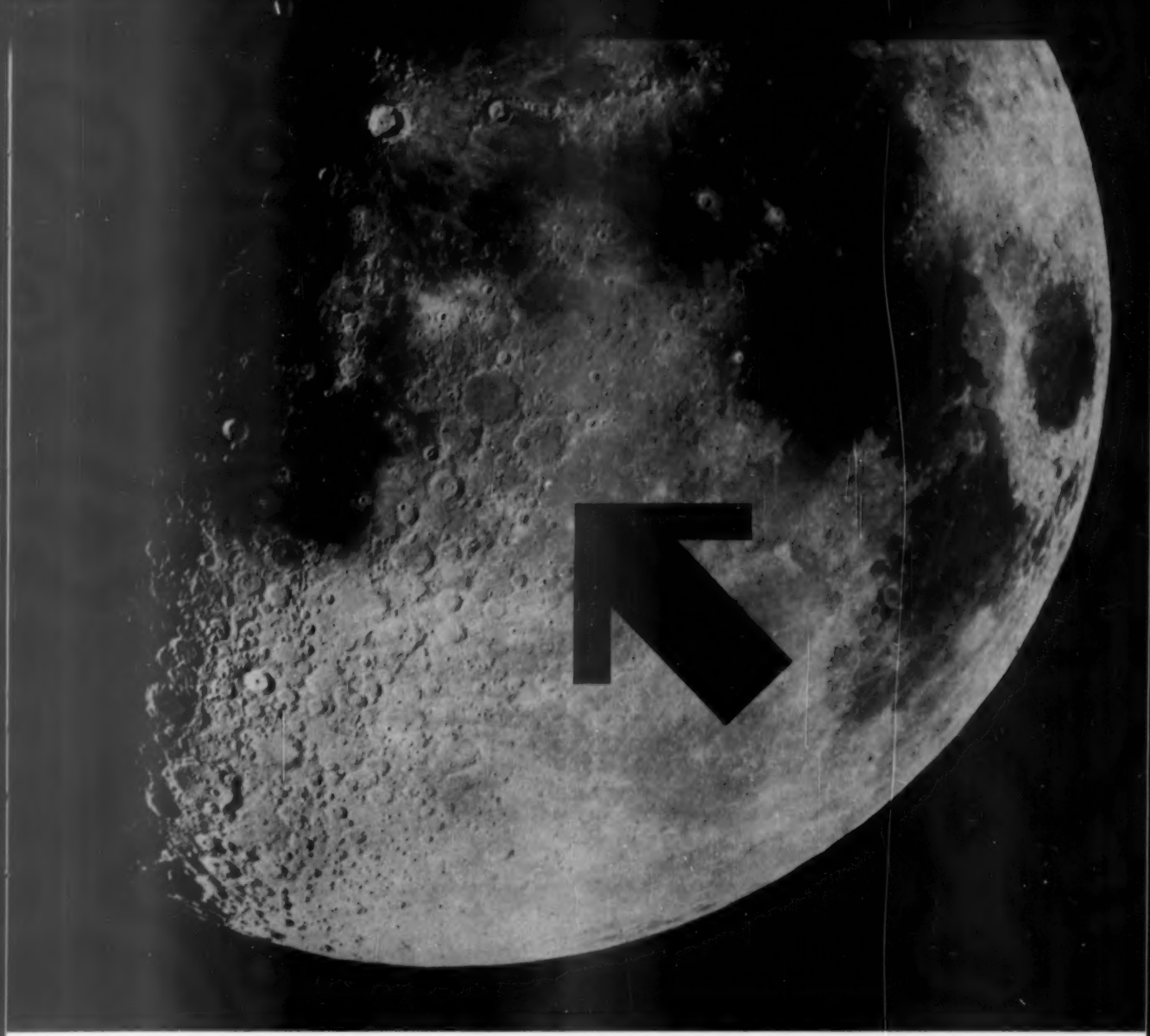
If the test aliquot contains $>1$ $\mu$g of the element, plating is continued and the test for completeness of deposition is carried out at 15-min intervals until a satisfactory test is obtained.

The adequacy of the completeness tests was determined by adding the appropriate amount of carrier to the residual plating solutions and plating again. The residual radioactivity in these samples was in agreement with that predicted by the tests. The limits of the tests were chosen to represent a deposition of $>99.5\%$ of the sample.

## Sample Characteristics

The cobalt samples from either procedure are formed as bright-gray, hard uniform deposits. After a period of a few weeks, an oxide coating dulls the brightness of the samples but does not affect the counting rate significantly.

The zinc samples are formed as dull, bluish-gray, hard uniform deposits;



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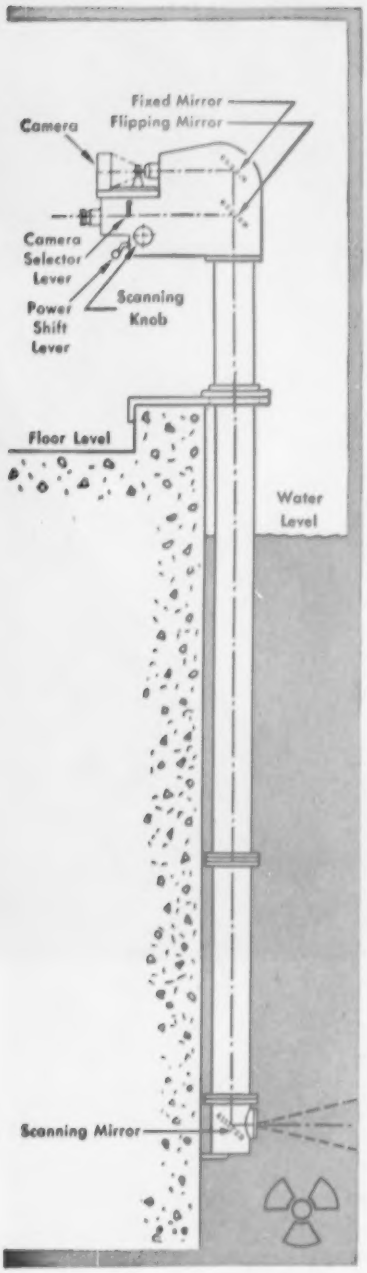


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the appearance of the samples changes slowly, darkening over a period of 2–3 months and eventually becoming black. During this time the counting rate does not change significantly, but it does show a 1–2% decrease by the time the samples become very black. The samples then look as though they were covered with carbon black but the coating is firmly adherent.

The iron samples are formed as bright, light-gray, hard uniform deposits. After a period of a few weeks, an oxide coating dulls the brightness of the samples but does not significantly affect the counting rate of either $Fe^{59}$ or $Fe^{55}$. Over a period of 1–2 months, the oxide coating reduces the counting rate of $Fe^{55}$ by $\sim$2%. There is no further reduction in the counting rate if the samples are kept in a clean dry storage area.

The uniformity of deposition within a sample varied by $\leq$10%, as determined by numerous autoradiographs of each sample type.

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The electroplating cell has evolved through a number of intermediate stages to the form now considered satisfactory.

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## Electroplating Unit

The electroplating unit consists of a bank of six cells, cell holders, stirrer motors, current controls, and an ammeter. One cell assembly is shown in Fig. 2.

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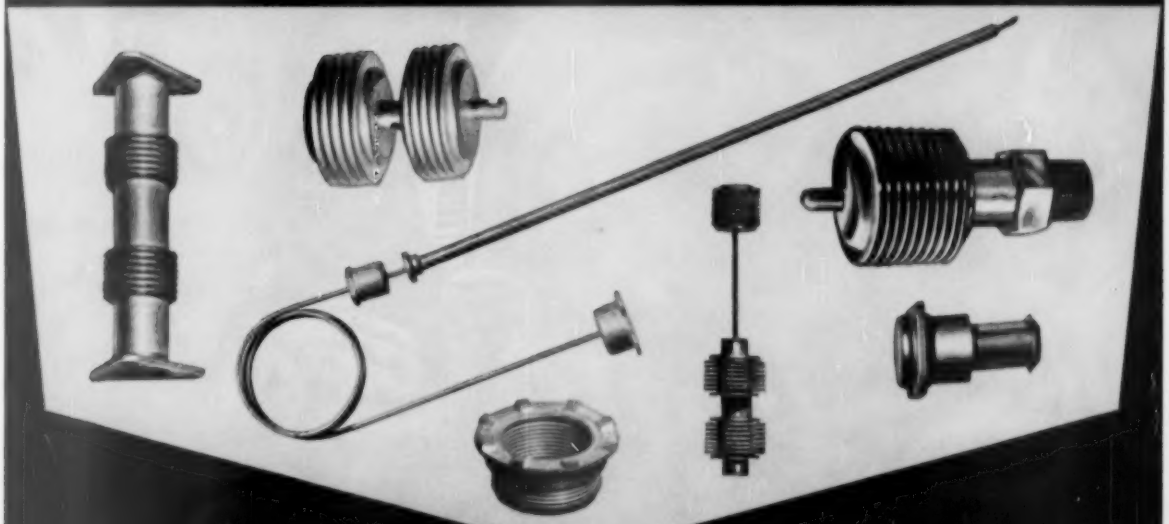

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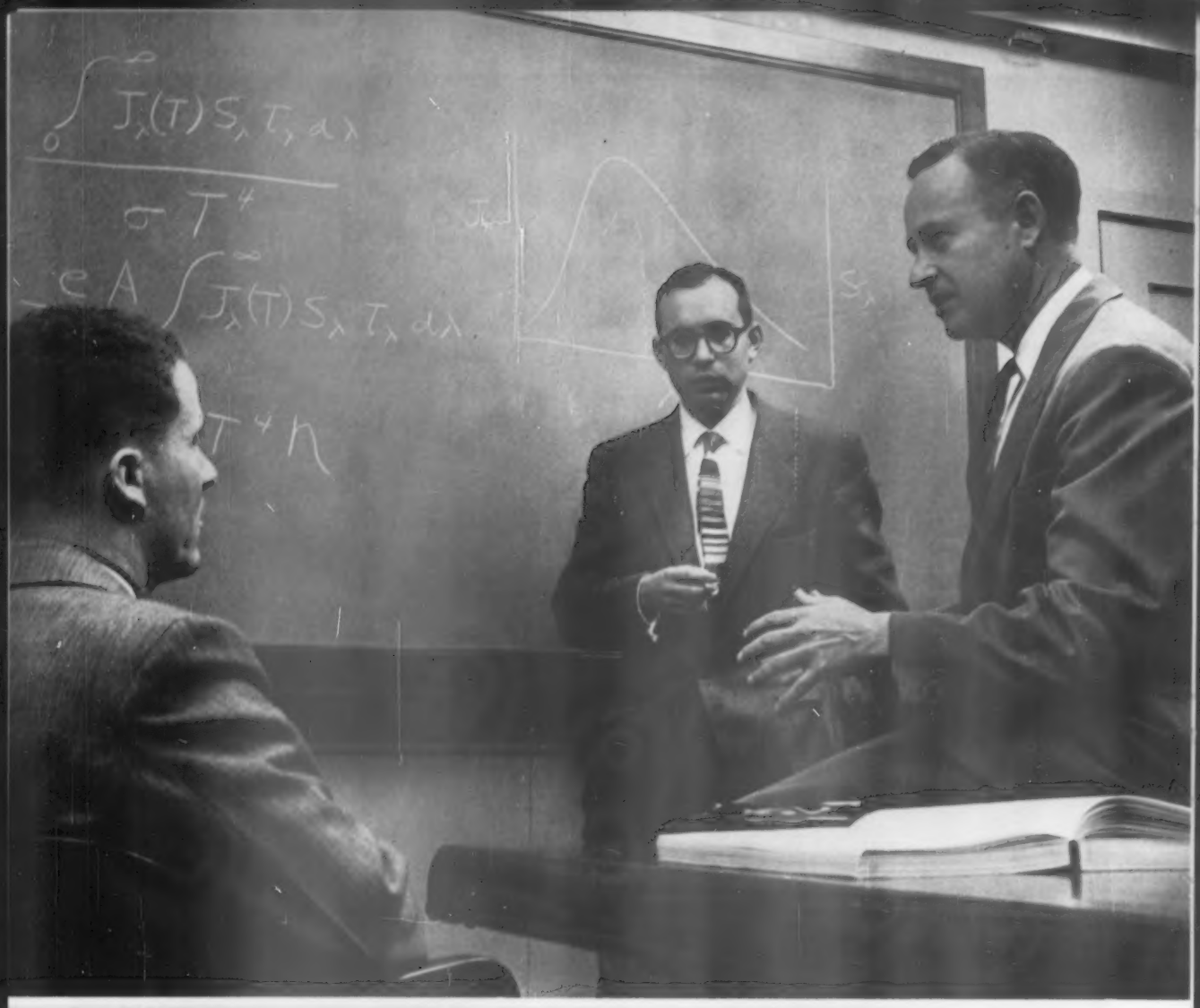

*Dr. Lewis Larmore (right) discusses fundamental problems of radiation transfer in infrared detection with Dr. T. Teichmann (center) and Experimental Physicist Freeman Hall.*

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* * *

*We wish to acknowledge the help received from Dorothy Kuchta, Hilda Yee, Ann Thompson, Jean Claflin, Mary Lou Foss, and Sidney Millen. This work was supported in part by a grant from the National Institutes of Health and by contracts with the Office of Naval Research and the U. S. Atomic Energy Commission.*

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# Remelting May Permit Reclaiming Uranium-Contaminated Metals

By P. B. KLEVIN and W. B. HARRIS

*Industrial Hygiene Branch, Health and Safety Laboratory*

*U. S. Atomic Energy Commission, New York, New York*

Since AEC policy now permits free disposal of uranium-contaminated ferrous steel if certain radioactivity restrictions are met, it is our belief that, properly handled, other metals and contaminations can be safely included in the disposal policy.

Previous policy permitted introducing no measurable quantity of radioactive material into the environment. Thus, vast stores of contaminated iron and steel accumulated. Reprocessing this metal into new steel demonstrated that, within certain limits, uranium-contaminated iron and steel could be released into normal trade channels without prejudice. But contaminated materials other than carbon steel are being accumulated in large amounts.

To obtain information that might further liberalize disposal regulations, a study was undertaken covering uranium-contaminated nickel, stainless steel, copper, and aluminum scrap. The purpose has been:

**1.** To determine the amount of uranium that might be picked up by scrap metal under various conditions of service.

**2.** To determine the effect of remelting this scrap.

**3.** To determine the residual uranium in remelted metal.

**4.** To determine if material treated in this manner can be sold into normal commercial channels without adversely affecting industry or the public health.

Uranium-contaminated scrap was obtained from various AEC feed-materials (natural uranium) production sites. In addition, standard samples of each of these metals were obtained from the National Bureau of Standards. Surface measurements for alpha activity were made on all pieces using Samson and Juno ionization-chamber de-

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tection instruments. Smear samples were taken from the surface of the scrap pieces and counted for alpha activity. Drillings were made through the pieces and analyzed photofluorimetrically for uranium content. After sampling and measurement, the contaminated metal was remelted in a manner similar to that used industrially in treating scrap.*

Stainless-steel, copper, nickel, and nickel-steel ingots were made by melting 20–30 lb of scrap in a magnesia or clay graphite crucible and casting into molds. The melting was done in a high-frequency furnace at several hundred degrees above the melting temperature of the metal concerned. The melting temperatures of the metals were 400–600° F greater than the remelting temperature of uranium (2,100° F). The pour-stopper rod and the dross or slag containing the impurities were separated from the ingot and saved for analysis.

The aluminum melt was made by melting 30 lb of contaminated scrap in a silicon carbide crucible at 1,400° F, using a carbureted natural-gas-fired furnace. This melt was not cast but allowed to solidify in the crucible. The top 1 in. of the aluminum ingot was slag.

Each of the melts took place in an area where no ventilation other than natural draft was available. Air dust samples were taken directly above the crucibles to evaluate the health hazard of uranium-carrying dust.

After remelting, surface alpha-activity measurements were made on the individual ingots and on the slag when possible. Duplicate samples were obtained from all sides of the remelted ingot by random drilling to ½ and 1½ in. depth and from the slag from each melt. These samples were analyzed fluorimetrically for uranium content. The results of all measurements are presented in Tables 1–5.

## Air Contamination

Air-dust samples revealed that no hazard should exist from dust or fumes during such remelting operations. With a single exception, all samples taken during the remelting processes indicated atmospheric uranium concentrations below 10 dpm/m³ or less than 1% of the maximum permissible concentration.

The one high sample showed a concentration of 80 alpha dpm/m³. Inasmuch as these samples were taken in the gas stream directly over the furnace, it can be assumed that even the remelting of large quantities could be safely accomplished.

## Conclusions

1. Sheet metal ⅛–¼ in. thick, the surface of which is contaminated with uranium, but otherwise relatively clean, can be expected to contain on its surface 1–10 mg of uranium per gram of metal.

2. The uranium surface contamination can be removed from stainless, nickel, and copper, down to approximately 1 part per million by remelting.

3. Aluminum scrap that was similarly contaminated did not respond successfully to this treatment. The poor results might be attributed to aluminum's preferential absorption of oxygen in the presence of almost any other metal, including uranium. Therefore, oxidation cannot be expected to be used successfully for slagging the uranium out of aluminum. It has been suggested that fluoride slagging might be more effectively applied for remelting aluminum.

4. The remelted nickel, nickel stainless, and copper showed residual uranium contamination comparable to the pre-1942 NBS standards. The maximum deviation from this was found in the stainless steel; drillings at ½ in. showed considerable residual activity, while drillings at 1½ in. showed less than 1 μg U/gm. Since remelting this metal brings the uranium content down to 1 μg/gm or less, the remelted material cannot be considered hazardous.

5. The remelting of this type of material can be accomplished without hazard to personnel.

6. The contaminated slag may warrant reprocessing for recovery of the uranium. However, if this should not prove economical, the fact that this slag contains significantly less uranium than a very low-grade ore, such as phosphate rock, should permit the material to be disposed of on the normal slag dumps.

* * *

*The authors wish to acknowledge assistance rendered by colleagues in the U. S. Atomic Energy Commission and by Commission contractor personnel. In particular, John Alercio, James E. McLaughlin, Jr., Clement Rodden, and John Harley of the AEC and Lewis Barclay, Harshaw Chemical Co., and Mont Mason, Mallinckrodt Chemical Works, made important contributions to the study.*

* Titanium Alloy Manufacturing Div., National Lead Co. (Niagara Falls, N. Y.), and the American Smelting and Refining Co.'s Central Research Laboratories cooperated in processing the metal.

## Results of Decontamination by Remelting Uranium—Contaminated Scrap

| Sample description | Direct radiation measurements (α-dpm/100 cm²) No. of readings | Aver. | High | Low | Smears (α-dpm/100 cm²) No. of smears | Aver. | High | Low | Analytical results (μg U/gm) No. of drillings | Aver. | High | Low |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nickel** | | | | | | | | | | | | |
| Contaminated scrap | | | | | | | | | | | | |
| Tray ⅛ in. thick | 90 inside | 48,200 | 73,000 | 24,000 | 20 | 2,780 | 5,290 | 921 | 50 | 5,775 | 6,050 | 5,500 |
| | 90 outside | 21,300 | 26,500 | 15,500 | | | | | | | | |
| Receivers ¼ in. thick | 10 inside | 17,500 | 18,750 | 15,600 | 2 | 71 | 109 | 33 | 50 | 2,925 | 3,000 | 2,850 |
| 4 × 4 × ¼ in. | 10 outside | 6,250 | 6,800 | 6,000 | | | | | | | | |
| Remelt | | | | | | | | | | | | |
| ½-in. drillings, all surfaces | 10 | 120 | 200 | 100 | 4 sides | 13.1 | 16.4 | 9.2 | 24 | 1.15 | 1.4 | 0.9 |
| 1½-in. drillings, all surfaces | 10 | 120 | 200 | 100 | 1 bottom | 9.7 | 9.7 | 9.7 | 24 | 1.25 | 1.6 | 0.9 |
| Slag from melt | | | | | | | | | | | | |
| Drilling through top slag | | | | | | | | | 11 | 1,460 | 1,760 | 1,160 |
| Drilling through bottom slag | | | | | | | | | 11 | 3,380 | 4,250 | 2,500 |
| Drilling through pour-stopper rod | | | | | | | | | 4 | 1,050 | 1,050 | 1,050 |
| NBS nickel (pre-1942) | | | | | | | | | 3 | 0.14 | 0.2 | 0.1 |
| **Nickel stainless (3 lb nickel, 27 lb stainless and chromium)** | | | | | | | | | | | | |
| Contaminated S. S. scrap ¼ lb. and ⅛ in., 4 × 4 in. scrap | | | | | | | | | | | | |
| Top | 64 | 1,800 | 8,750 | 375 | 4 | 58 | 97 | 42 | 49 | 77 | 79 | 63 |
| Bottom | 64 | 6,850 | 26,800 | 500 | 4 | 297 | 530 | 133 | | | | |
| Contaminated nickel receivers | 20 | 11,900 | 18,750 | 6,000 | 2 | 71 | 109 | 33 | 50 | 4,300 | 6,050 | 2,850 |
| Remelt | | | | | | | | | | | | |
| ½-in. drillings, all surfaces | 12 | <100 | <100 | <100 | 4 sides | 3.0 | 5.0 | 0 | 27 | 0.95 | 1.2 | 0.7 |
| 1½-in. drillings, all surfaces | 12 | <100 | <100 | <100 | 1 bottom | 6.4 | 6.4 | 6.4 | 27 | 0.5 | 0.6 | 0.4 |
| Slag from melt | | | | | | | | | | | | |
| Drilling through Ni S slag | | | | | | | | | 10 | 135 | 150 | 120 |
| Drilling through Ni S stopper rod | | | | | | | | | 4 | 190 | 220 | 140 |
| NBS Ni S. S. (pre-1942) | | | | | | | | | 3 | 0.5 | 0.5 | 0.5 |
| **Stainless steel** | | | | | | | | | | | | |
| Contaminated scrap | | | | | | | | | | | | |
| Top | 64 | 1,800 | 8,750 | 375 | 4 | 58 | 97 | 42 | 45 | 71 | 79 | 63 |
| Bottom | 64 | 6,850 | 26,800 | 500 | 4 | 297 | 530 | 133 | | | | |
| Remelt | | | | | | | | | | | | |
| ½-in. drillings, all surfaces | 12 | 100 | 120 | 75 | 4 | 10.5 | 15.7 | 8.0 | 22 | 50.5 | 83 | 18 |
| 1½-in. drillings, all surfaces | 12 | 100 | 120 | 75 | | | | | 22 | 0.65 | 0.7 | 0.6 |
| Slag from melt | | | | | 3 | 4.8 | 6.3 | 3.7 | Entire sample | 51.5 | 61 | 42 |
| NBS sample (pre-1942) | | | | | | | | | 3 | 0.23 | 0.3 | 0.2 |
| **Aluminum** | | | | | | | | | | | | |
| Contaminated Al scrap 4 × 4 in. and 18 × 18 in. pieces | | | | | | | | | | | | |
| Top | 56 | 8,245 | 18,000 | 1,530 | 5 | 50.9 | 94.3 | 10. | 58 | 4,980 | 6,500 | 3,450 |
| Bottom | 56 | 4,450 | 7,500 | 1,625 | 5 | 45.8 | 61.7 | 24.6 | | | | |
| Remelt | | | | | | | | | | | | |
| ½-in. drillings, bottom & sides | 25 | 3,870 | 6,800 | 2,000 | 3 bottom | 16.4 | 25.3 | 10.3 | 18 | 2,150 | 2,400 | 1,900 |
| 1½-in. drillings, all surfaces | 25 | 3,870 | 6,800 | 2,000 | 2 sides | 10.4 | 13.7 | 6.3 | 36 | 800 | 1,000 | 600 |
| Slag from melt (top 1 in.) | 18 | 4,625 | 6,500 | 3,700 | 3 | 17.1 | 20.9 | 13.1 | 18 | 2,700 | 3,200 | 2,150 |
| NBS Al (pre-1942) | | | | | | | | | 2 | 0.65 | 0.8 | 0.5 |

(continued on p. 96)

**Results of Decontamination by Remelting Uranium—Contaminated Scrap** (*Continued*)

| | *Direct radiation measurements* | | | | *Smears* | | | | *Analytical results* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Sample description* | *No. of readings* | *Aver.* | *High* | *Low* | *No. of smears* | *Aver.* | *High* | *Low* | *No. of drillings* | *Aver.* | *High* | *Low* |
| **Copper** | | | | | | | | | | | | |
| Contaminated scrap | | | | | | | | | | | | |
| Slightly contaminated | | 800 | 1,750 | 300 | | | | | | | | |
| Moderately contaminated | | 4,000 | 6,000 | 2,100 | | | | | 69 | 1,663 | 3,360 | 5.4 |
| Grossly contaminated | | 12,000 | 20,000 | 8,000 | | | | | | | | |
| Remelt | 24 | <100 | <100 | <100 | | | | | 3* | 0.37 | 0.5 | 0.3 |
| Slag from melt | | | | | | | | | 8 | 8,480 | 2,350 | 504 |
| NBS copper (pre-1942) | | | | | | | | | 3 | 0.2 | 0.2 | 0.2 |

* Composite of 24 samples analyzed showing <0.001% $U_3U_8$ or <8.4 μg U/gm copper.

# Effect of Radiation on a Lucite Radium Applicator

By **BERNICE B. BORRMAN*** and **MARTIN VAN HERIK†**
*Mayo Clinic and Mayo Foundation‡*
*Rochester, Minnesota*

Effects produced by relatively high-intensity radiation from neutron and gamma sources on various plastic materials have been described elsewhere (*1*, *2*). We have noted some of these same effects from comparatively low-intensity radium gamma rays.

A Lucite (methyl methacrylate) radium surface applicator (Fig. 1) had been made up for emergency use with four 50-mg radium tubes (1.20 cm active length, 0.1-cm Pt filter) and placed in the radium safe at room temperature. When the applicator was dismantled approximately one year later, distinct cleavage patterns in the Lucite were observed in rather localized areas around each of the radium tubes. A piece of Lucite under one of the tubes fell away from the applicator when it was removed.

Although there might be some question that this cracking was due to machining rather than to radiation, the report by Bopp and Sisman (*1*) indicated that cracking could be expected from this quantity of radiation.

FIG. 1. Cracked Lucite about one of the four radium tubes on the circular applicator

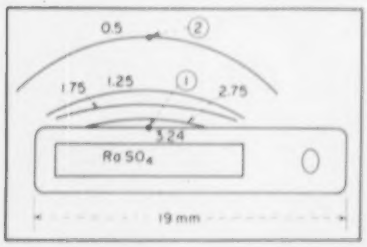


FIG. 2. Isodose curves around one radium tube (unit is $10^7$ rads). Total doses to points 1 and 2 were $3.1 \times 10^7$ and $0.64 \times 10^7$ rads, respectively, with dose rates of $3.5 \times 10^3$ and $7.3 \times 10^2$ rads/hr, respectively. The other three tubes contributed 2% and 19% of the doses at points 1 and 2, respectively

* Section of Biophysics and Biophysical Research.
† Section of Therapeutic Radiology.
‡ The Mayo Foundation is part of the Graduate School of the University of Minnesota.

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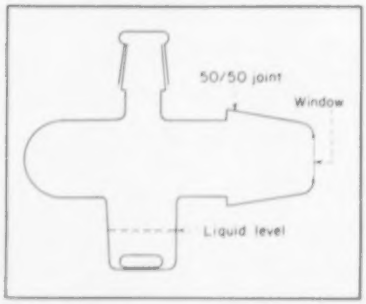
# Reaction Chamber for Isotopic Exchange Reactions

By **ROWLAND E. JOHNSON**
*Department of Chemistry*
*Florida State University*
*Tallahassee, Florida*

The usual experimental procedures in radioisotopic exchange reactions are tedious and time consuming and only a limited number of points can be taken with a resultant loss in precision. We have developed a reaction chamber that is applicable to many systems and that allows continuous monitoring of the reaction mixture to measure the exchange rate.

If the reaction is run in solution between two reactants, one of which is appreciably volatile, then the vapor phase will show a loss or gain of radioactivity as the exchange proceeds. Further, the rate of the change of activity will be proportional to the reaction rate, as measured by the fraction of




REACTION CHAMBER used for $Cl^{36}$ exchange studies. Window, about 5 mg/cm², decreases counting rate about 15% from zero-thickness window

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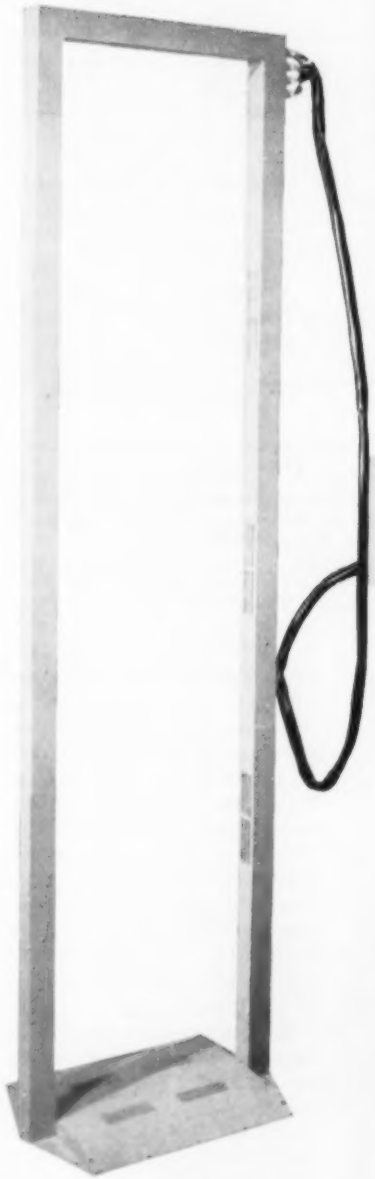

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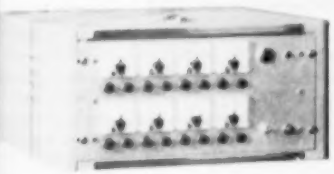

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radioactive equilibration. Our reaction chamber, one form of which is shown in the diagram, allows a continuous determination of fraction of exchange.

The chamber is constructed from an inner-member 50/50 tapered-stopper Pyrex ground-glass joint whose end has been heated and blown in slightly. The window, a portion of a glass bubble, is cemented in place with Araldite.* A $1\frac{9}{58}$ tapered-stopper joint is provided to introduce reactants. A magnetic stirring bar agitates the liquid; note that the solution cannot "see" the window. To count the radioactivity, we use an end-window Geiger-Muller tube.† This system is similar to that proposed by Norris.‡ Analysis of the counting data and calculation of the fraction exchange is done in a conventional manner.

For a very fast exchange reaction, it may take an appreciable time to establish equilibrium between the vapor and liquid phases. Preliminary experiments with $Cl_2$ in carbon tetrachloride show a half-time of about 2 min to establish equilibrium. Hence, this method might safely be used with reactions whose half-times are as short as 10 min. If the exchange rate is slow compared to the time required for equilibration of vapor and liquid, the only effect is a displacement of the curve of exchange *vs.* time on the time axis and an apparent negative fraction exchange at zero time.

* * *

*This work was performed under the auspices of the U. S. Atomic Energy Commission.*

* CN-501, Ciba Company, Inc., New York, N. Y.

† T G C-2 tube, Tracerlab, Inc., Boston, Mass.

‡ T. H. Norris, *J. Am. Chem. Soc.* **74**, 2396 (1952).

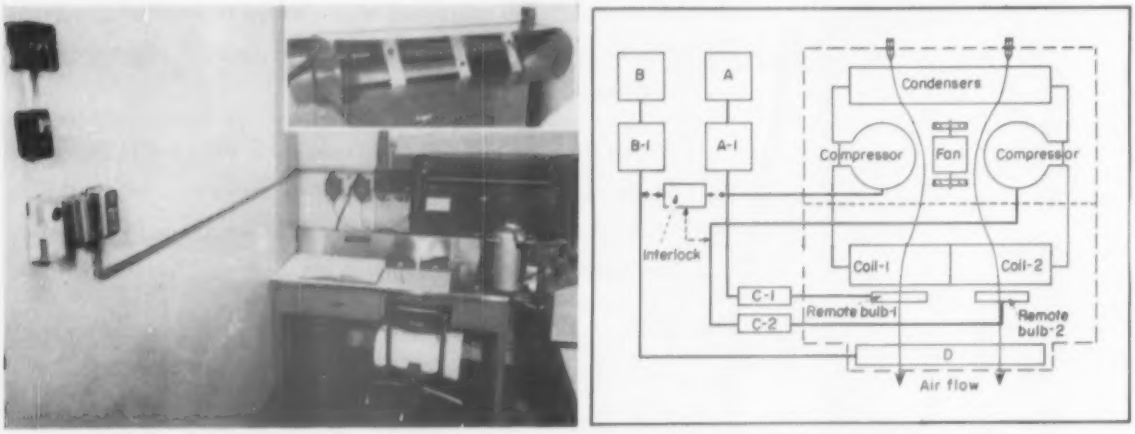


FIG. 1. Humidity- and temperature-control system is based on window-mounted commercial air-conditioning unit. Added components are Humidistat and relay (A, $A_1$), thermostat and relay (B, $B_1$), remote temperature-sensing bulbs at coils and exterior and safety switches (C-1, C-2), strip heaters (D), and safety interlock system between fan, compressor, thermostat, Humidistat, and heaters. Humidistat controls compressor operation—cooling coils below dew point and extracting air moisture. Thermostats simultaneously raise cold air to comfort temperature through strip heaters for 15–20° gradient, thereby reducing relative humidity. Remote bulbs prevent coil freeze-up by off-on cycle at 35–45° F. Wall-mounted Humidistant and thermostat should be 10 ft from unit for good response. Insert (left) shows strip heaters with louvered outlet of discharge vent removed; vent is only alteration in outside dimensions

# Humidity and Temperature Control Unit for a Counting Room

By L. E. PREUSS
*Edsel B. Ford Institute for Medical Research Detroit, Michigan*

The counting room (*1*, *2*) in the small radioactivity laboratory (*3*), in itself a relatively new and unique architectural entity, has design demands that include such usual considerations as a good electrical power supply, adequate light, and tables for computation (*4*). Over and beyond these routine facilities (*5*, *6*) the assay room occasionally requires provision for humidity and temperature control. The first minimizes high-voltage leakage across insulators (*7*, *8*) and the second is related to this leakage problem and to the equilibrium temperature of electrical circuits. Such a control system, developed for our counting room, is described here (Fig. 1).

The summer conditions of this locale included varying periods of high relative humidity, frequently in the 90's, accompanied by corresponding high temperature. During these times the background counting rate was two or three times the normal values with corresponding difficulty in the assay of low-level specimens. This familiar effect was particularly troublesome in experimental set-ups or where very high voltages were used. The humidity problem was compounded with several operators in the counting room. This is probably true of most counting areas (*9*, *10*) since these rooms are ordinarily small and are frequently closed off from the rest of the isotope laboratory. The counting room (*11*) under consideration here was 7 × 14 ft and 10 ft high.

Although good circuit-component design in isotope assay ordinarily precludes humidity-induced spurious counting, experience has shown that older and heavily used commercial units frequently reflect the high relative humidity by increased spurious counting. Our beta-ray assay of deli-

quescent samples by the dry-planchet technique as well as high-sensitivity electrometer work were affected by high humidity.

### Air Conditioning Units

Two types of basic units are available for the small isotope laboratory (*12, 13*).* The first is a water-cooled type in which condensing-coil heat is dissipated by tap-water flow. This set-up is large, takes up working floor space, requires plumbing, and generally is costly. Such a unit is efficient in extracting air moisture but this condensation must be removed by special plumbing.

The second type is the familiar window model with the condenser coils outside the room and cooled by air at outside temperature. Moisture on the cooling coils is sump collected and atomized against the condensers for improved heat transfer. Recirculated air passes through filtering and over the cooling coils. Fresh air from the condenser section is mixed with it at the filter. Such moisture extraction is advantageous, but unfortunately for this usage, circulated air passes the condensed water surface on the cooling coils saturating the air. This inexpensive conditioner uses no floor space, is

* "Small radioisotope laboratory" refers to organizations of 10 or less personnel. The counting room described houses a maximum of 4 or 5 technicians.

**Component List for Modified Unit**

| *Block Diagram (Fig. 1)* | *Description* |
|---|---|
| Basic Unit | Frigidaire ARO-100-21, two-compressor unit, 230 volts |
| A | Minneapolis-Honeywell Humidistat, wall type H 63A1x3 115, 230 volts, a-c |
| A-1, B-1 | Minneapolis-Honeywell relay type R 182A1CMOA2 |
| B | Minneapolis-Honeywell mercury-switch thermostat, wall type T 42H1x2, 115-230 volts, a-c |
| C-1 and C-2 | Minneapolis-Honeywell temperature controller with remote sensing bulb T 415B300XA3 |
| D | Two series-operated heaters—Chromoalox model S-1807, 230 volts, 60 cycle, 750 watts each |


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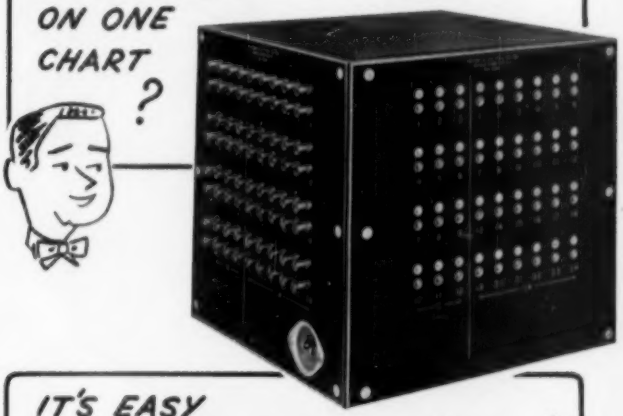

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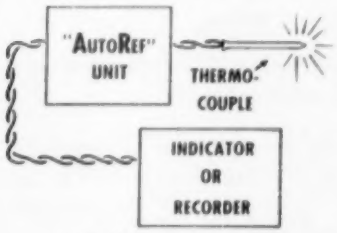


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simply installed, and was selected because of its good prospects for alteration and adaptability for the small operation.

This model (see component list), with optional remote thermostat control, has a 9,900-Btu/hr capacity with 50 ft³/min of fresh air for ventilation. It uses two ½-horsepower condensing units usable in "either or both" combinations.

**Operation of basic unit.** Initial testing of the unaltered, installed unit demonstrated that it could not fill the special requirements of humidity control for the isotope assay area (Fig. 2). The presence of several operators in the assay room heightened the relative humidity and caused severe fluctuations.

With continuous operation, the unit tended to freeze condensed moisture on the coils at night or in mild weather and eventually to block the air flow through the unit. This formed a continuous cycle with the thermostat recognizing only the increased room temperature and, therefore, signaling for increased operation of the unit. This resulted in a flood of water from melted ice when the unit was turned off.

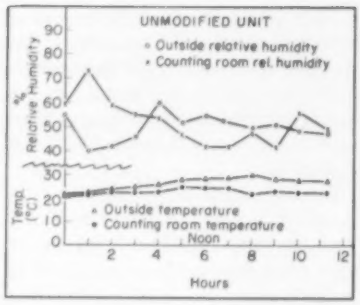
**Alteration of unit.** The control requirements were: continuously variable humidity control down to 35% relative humidity, temperature control throughout the range of the unit (from 60° F up), all with a maximum acceptable variation of 5% and allowing for up to 4 persons in the counting room and frequent opening of the doors.

Figure 1 shows the added components used in alteration.

## Cycle of Operations

Following Fig. 1, the mode of operation is as follows: The unit is started using the normally furnished on-off controls. The Humidistat and associated relay (A and A-1), in accordance with the Humidistat setting, start the cooling unit to provide a dynamic room condition. This circuit is not energized if the fan is inoperative or stops in mid-operation because of the circuit interlock with the blower's circuit. This safety precludes excessive refrigeration of the cooling coils and consequent freezing of condensed moisture. This will discharge coil air at low and uniform temperature (above 35° F); thus, a reheat is necessary.

The thermostat and associated relay, operating the electrical heaters only, reheat the discharge air by means of strip heaters to maintain the desired room dry-bulb condition. This circuit



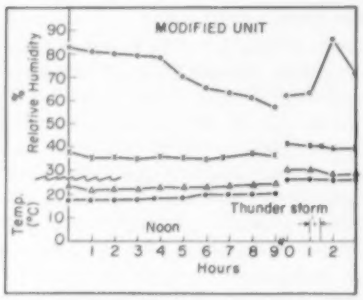




FIG. 2. Humidity and temperature control of commercial unit before and after alteration. Although temperature control of unmodified unit was acceptable, humidity control was erratic; increased humidity at 0–4 and 10–12 hr was caused by cool-air flow over wet cooling coils and exhaust of this near-saturated air into room. Modified unit shows adequate suppression of temperature and humidity fluctuations, particularly during thunder shower; during latter period, controls were set higher—room-humidity fall reflects reduced personnel number

is also interlocked with A and A-1 so that it is energized only if the cooling equipment is on. This obviates excessive temperature in the heater area should the cold-air flow be shut off by some contingency such as heavy rhime ice on the cooling coils. This is also interlocked to compressor 2 and is dependent upon A and A-1 and the blower function. The reheat reduces the relative humidity and introduces ~60° F air into the room, thus allowing for a 15° to 20° F diffusion temperature gradient.

Thermostatic safety switches (C-1 and C-2) automatically stop the unit upon overheating, opening all the circuits through the electrical interlock. This is a secondary safety to obviate overheating as well as overcooling or flooding. Operation is restored automatically when normal conditions prevail. Setting for C-1 and C-2 are: off = 35° F, on = 45° F. These controls are effective in preventing icing. The unit's on-off switch de-energizes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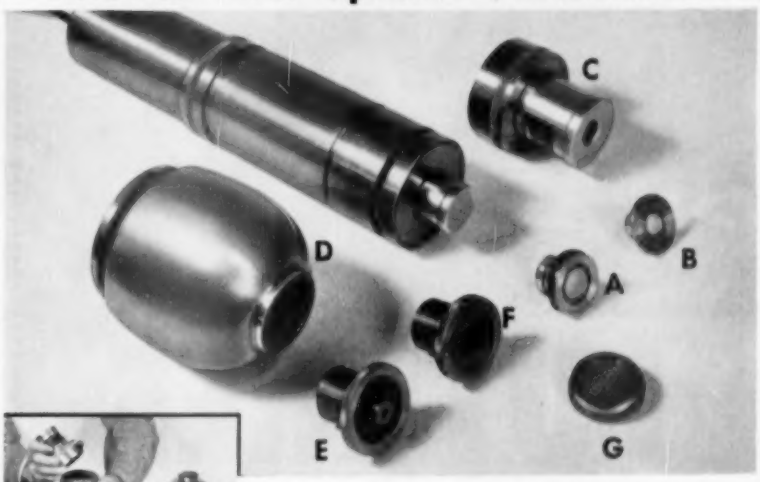


Optional accessories include (A) ¾", (B) ½", and (C) well scintillation crystals. Large lead collimator (D) provides exceptional side shielding, accepts 20° flat field collimator (E) or special focusing collimator (F). Alpha and beta phosphors (G) are interchangeable with standard 1" crystal.

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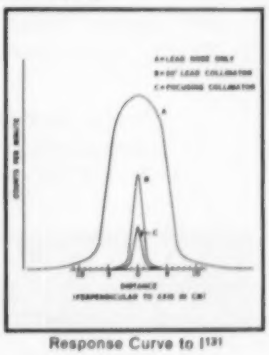
**Operation** (with 1" x 1" crystal)—Plateau: 250 volts; 2% slope/100 volts. Background: Crystal exposed—1250 cpm; with lead nose—160 cpm; with additional collimation—95 cpm. Detection efficiency (1 microcurie $I^{131}$ at 10 cm): 4400 cpm.



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all the components including fan, heaters, compressors, thermostatic controls, and relay power. Where a single cooling system is used instead of the double one described, only one low-limit thermostat and remote bulb will be required.

The set-up was initially tested without the C-1 and C-2 safety switches. Since the coils occasionally froze up at night when the outside air temperature dropped, operation without C-1 and C-2 is not advisable.

## Air Flow

The air flow is conventional with one exception. Intake is largely recirculation from the room with a fraction of outside air added to insure freshness. The air passes over the cooling coils, which are below the dew point, and through the blowers. The excess air moisture, thus condensed, is drained outside through special drip holes in the base plate. Air circulation now departs from the conventional. After leaving the cooling coils, the air flows over the remote bulbs and, if cooling has been excessive, C-1 and C-2 come into operation to act to turn off one or both condensers and simultaneously to open all electric circuits. The air flow next is directed over the heater coils and is discharged out of the port into the room. These strip heaters raise the air to comfort temperature, at the same time reducing the relative humidity to desired levels.

The Humidistat and thermostat are located at the far end of the room to provide for air mixing before sampling. The thermostat gives the proper signal to the strip heaters to introduce air at about a 15° F gradient to room temperature. The temperature of the air leaving the coils, on the other hand, can be as low as 35° F before reheat.

## Operation

Routine use of this design has demonstrated its reliability in holding constant temperature and humidity. Figure 2 (bottom) is a portion of a time-recorded plot of relative humidity. The small variations amount to less than 4% in each case. These are due to changes in the personnel present and irregular door openings.

## Summary

This altered unit has been in operation for three summers with demonstrated reliability. For large control changes, it was necessary for a day to elapse before the humidistat equi-

librated precisely. Certain limitations are placed on the maximum relative humidity by that available outside. The system has quick adaptability to changing personnel numbers, electrical circuits in operation, etc.

The unit's capacity should be chosen to exceed the room demands by a factor of two. This unit has carried the added volume of the adjoining room at times (*3*). The cost of the custom unit plus installation is about double that of the commercial unaltered conditioner. This is still much below that of commercial custom units.

The inclusion of a conditioner may inject some changes into the administration (*14*, *15*) of the isotope laboratory. Good ventilation (*16*) is a factor in radioisotope laboratory use and must be taken into consideration when using the conditioner. Since the counting room is usually closed off, the nature and handling of the specimens brought in for assay must be re-evaluated in the light of reduced air flush through the room.

* * *

*This is to acknowledge the valuable technical aid in design and installation of the altered unit by John Ancinec, Jr., Frigidaire Sales Corp., and Mr. Stanley J. Janczarek, Refrigeration Service, Inc., Detroit, Mich.*

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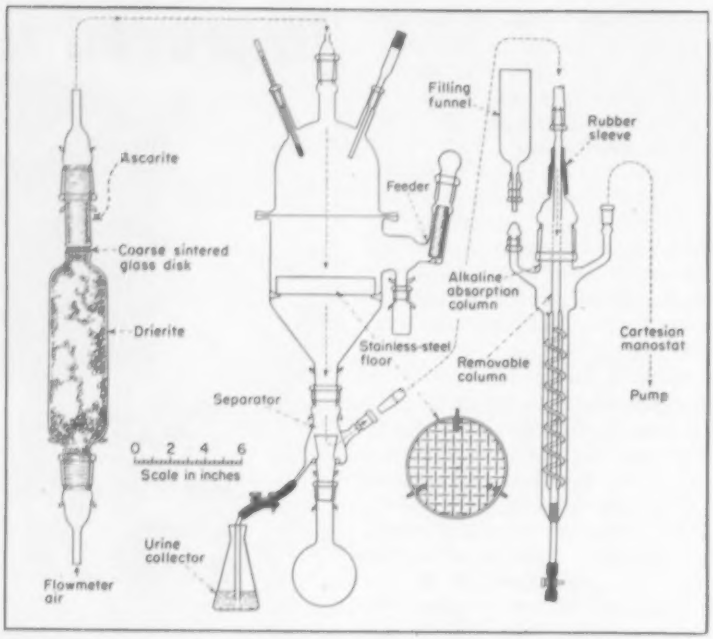


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# Metabolism Cage for Rats


By LLOYD J. ROTH
*Department of Pharmacology*
*University of Chicago*
*Chicago, Illinois*


It is frequently desirable to inject small animals with a carbon-14-labeled compound and to study its excretion pattern in the urine, feces, and the expired air. A previous publication described an all-glass metabolism cage for mice.* The cage described herein (see illustration) has been used successfully with rats. The ancillary equipment shown is designed to work with either cage system.

Toluene is used as a urine preservative in the collecting flask and also serves as an indicator for the system, which is under slight negative pressure. The urine-collector clamp is removed during operation unless solvents are to be avoided.

The feeding arrangement prevents mice and rats from bringing food into the cage if a hard stick is prepared for the feeder. This may be done by baking pulverized ration pellets mixed with raw egg as a binder. The trap in the feeder floor prevents pulling small crumbs into the cage.

A thermometer in the cage is essential. The temperature can be controlled with fans and moist towels under difficult weather conditions. It is best to operate a bank of three or four cages as a system with a volume pressure equalizer and a manostat set at a slight negative pressure of about 10 mm Hg below atmospheric. The rate of flow in each chamber can then be regulated with a pinchcock on the rubber tubing connecting the cage and the absorption column. The cage separator and floor can be removed for cleaning. The absorption towers are washed with diluted hydrochloric acid and water without disassembling.

* * *


*These cages and ancillary equipment were constructed in the glass shop at the University of Chicago by Christian C. van Hespen. The work was supported in part by grants from the U. S. Atomic Energy Commission and the Surgeon General of the Army.*


* L. J. Roth, L. Leifer, J. H. Hogness, W. H. Langham, *J. Biol. Chem.* **176**, 249 (1948).

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2. Reactors—Robert Loftness, North American Aviation, Inc.
3. High-Level Isotopic Sources—Otto A. Kuhl, Brookhaven National Laboratory
4. Low-Level Isotopic Sources—Irving A. Berstein, Tracerlab, Inc.
5. The Next Five Years—D. J. Hughes, Brookhaven National Laboratory

**TUESDAY, P.M.**

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SESSION II—Chemical Applications, CHAIRMAN—J. W. Kennedy, Washington University, St. Louis, Missouri

1. Radioisotopes in Inorganic Chemistry—A. C. Wahl, Washington University, St. Louis
2. Radioisotopes in Organic Chemistry—C. J. Collins, Oak Ridge National Laboratory
3. Radiation Induced Inorganic Reactions—S. C. Lind, Union Carbide and Carbon Corporation
4. Radiation Induced Organic Reactions—A. Bueshe, General Electric Company
5. The Next Five Years—J. J. Katz, Argonne National Laboratory

BANQUET

**WEDNESDAY, A.M.**

SESSION III—Biological Applications, CHAIRMAN—George V. LeRoy, University of Chicago

1. Sterilization and Pasteurization—W. Urbain, Swift and Company
2. Plant and Animal Development—Sheldon Wolff, Oak Ridge National Laboratory
3. Medical Studies—C. N. Rice, Eli Lilly
4. Radiation Hygiene—G. Failla, Department of Radiology, Columbia University
5. The Next Five Years—John C. Bugher, Rockefeller Foundation

SESSION IV—Industrial Applications, CHAIRMAN—Charles E. Crompton, National Lead Company

1. Isotope Dilution and Tracer Analysis—Charles Rosenblum, Chemical Division, Merck and Company, Inc.
2. Activation Analysis—C. Leddicotte, Oak Ridge National Laboratory
3. Thickness Gaging—George B. Foster, Industrial Nucleonics Corporation
4. Inspection and Radiography—D. T. Green, Picker X-Ray
5. Wear Studies Employing Tracers—M. Merchant, The Cincinnati Milling Machine Company
6. The Next Five Years—L. Reiffel, Armour Research Foundation

**WEDNESDAY, P.M.**

LUNCHEON—Address by Eugene Zuckert, consultant; formerly member of U. S. Atomic Energy Commission

SESSION V—Instrumentation, CHAIRMAN—W. A. Higinbotham, Brookhaven National Laboratory

1. Electronic Detectors—C. J. Borkowski, Oak Ridge National Laboratory
2. Nonelectronic Detectors—J. H. Schulman, Naval Research Laboratory
3. Laboratory Instruments—Hugh F. Stoddart, Atomic Instrument Company
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5. The Next Five Years—W. A. Higinbotham, Brookhaven National Laboratory

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# Two Viewpoints on Controlling Boiling Reactors

Is it worthwhile to compromise the basic simplicity of boiling reactors to ease the control problem? This is a question raised as a result of the article, "How to Control a Boiling Reactor," (see NUCLEONICS, December '55, page 42) by John MacPhee, project engineer, nuclear engineering laboratory, American Machine & Foundry Co., Greenwich, Conn. Here are comments on the article by R. Philip Hammond, Los Alamos Scientific Laboratory, University of California, Los Alamos, N. M., with responses by John MacPhee.

**Hammond.** The boiling reactor received immediate recognition when proposed because of its simplicity. A difficult control problem became apparent in power application studies. This has resulted in a number of suggested modifications of the original concept. As an observer not working in the field of boiling reactors, I view with alarm some of the proposed "improvements," such as dual loops, dual cycles, etc., which destroy the original simplicity of the system. It is my purpose here to point out that this simplicity is the strongest advantage of the boiling reactor, and that designers should not be lured into compromising this for the sake of a less difficult control problem.

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**MacPhee.** Space does not permit the detail necessary to do justice to the questions raised here nor is this writer best qualified to comment on the dual-cycle design. However, it should be pointed out that the selection of a power-reactor-plant cycle is determined in large measure by the intended application. For example, in a military application the choice of plant cycle is greatly influenced by reliability, ease of maintenance, and, in some cases, weight. On the other hand, in a central-station application economy and total power output are paramount. However, in all applications safety is a factor that cannot be treated lightly if the present hopes for nuclear power are to be realized. Therefore, the evaluation of a reactor design solely on the basis of an indefinable simplicity is not only difficult but may be deceiving.

As for one of the "improvements" mentioned by Mr. Hammond, the closed-cycle boiling reactor concept is not a compromise design but rather a design that eliminates the disadvantages of using radioactive steam in the turbine and auxiliaries while preserving the advantages of removing reactor heat with a recirculating boiling loop. To mention just one of the many resultant advantages, this design facilitates the use of a separate oil-fired superheater to improve the cycle efficiency. There are certainly many applications where this is desirable.

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**Hammond.** The article by John MacPhee (see NU, Dec. '55, p. 42) is a step in the right direction. He has returned to the basic arrangement of the system in his Fig. 5. The analysis of the control problem is sound, and two of his suggested solutions (Schemes 1 and 2) appear workable (the recirculating pump of his Scheme 3 would have to pump *vapor* through the core to effect any change in void fraction; this is an unlikely arrangement). But then he suggests the use of multiple controls, which is a major retreat from basic simplicity.

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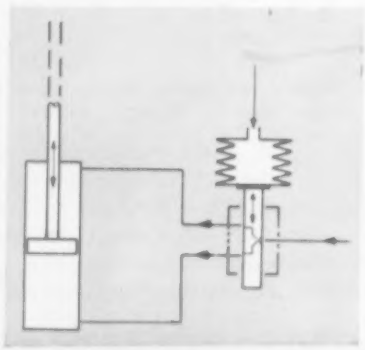

FIG. 1. Hydraulic amplifier for rod control

**MacPhee.** With regard to Mr. Hammond's statements, "the recirculating pump of Scheme 3 would have to pump *vapor* through the core to effect any change in void fraction. This is an unlikely arrangement." The above statements are not correct. In a recirculating system (i.e., not once-through), vapor fraction at any point in the core, and thus average vapor fraction, is determined by velocity of the water at the core inlet, power density, and pressure (pressure effects include slip). For constant pressure and power density, vapor fraction decreases as inlet velocity is increased. In Scheme 3, the inlet velocity is controlled by installing a pump in the downcomer, i.e., the return path of the liquid. Thus, varying the pump speed will vary the velocity of the water and thus vary the average vapor fraction. Note that the fluid in the pump will be in the liquid phase provided there is sufficient head above the pump to prevent flashing in the pump and that there is a negligible amount of vapor entrained in the downcomer.

Another way of expressing Scheme 3 is to say that the recirculation ratio of the boiling loop is controlled via forced circulation by a steam-pressure signal. Furthermore, many oil-fired boilers employ pumps in a similar manner to obtain forced circulation.

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**Hammond.** The essential facts, as have so often been pointed out, are that the boiling reactor is just critical at some relatively constant effective void volume, unless the control rod is moved, and that load changes tend to affect this void volume in the wrong direction. Therefore, two main approaches to control present themselves —move the control rod to compensate for load changes, or arrange the system so that load changes will give a reversed effect on effective void volume.

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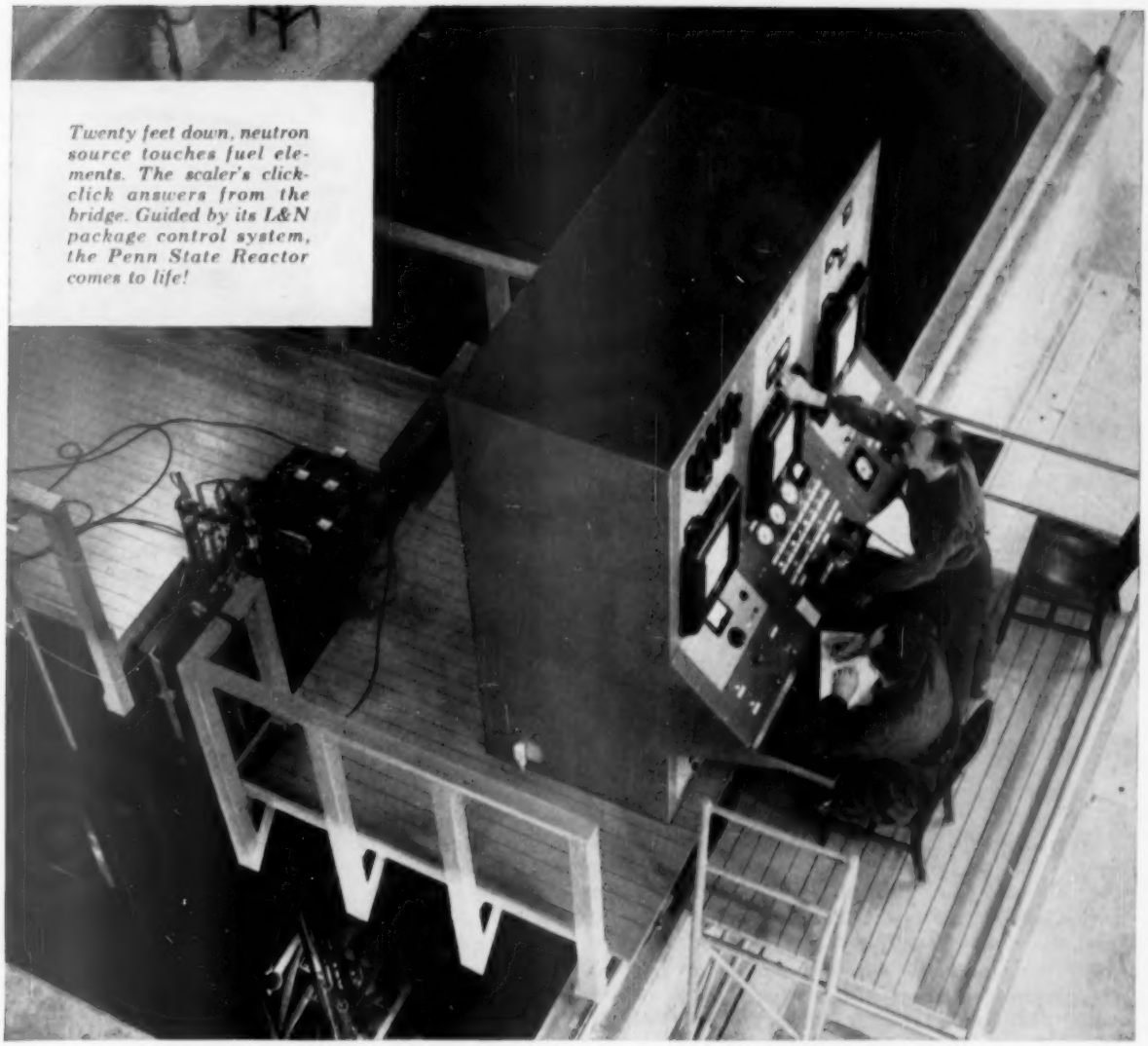
**MacPhee.** With regard to the statement, ". . . and that load changes



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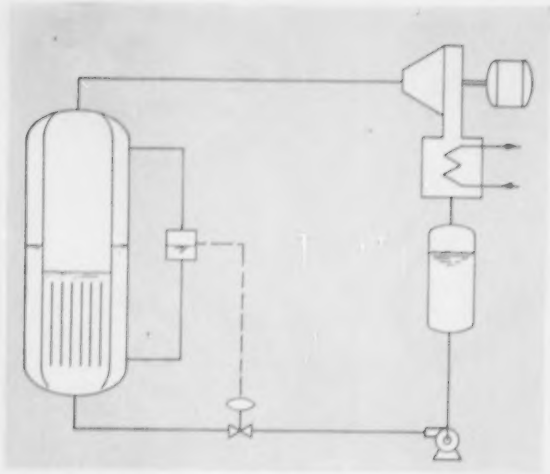

FIG. 2. Pressure control of feedwater flow

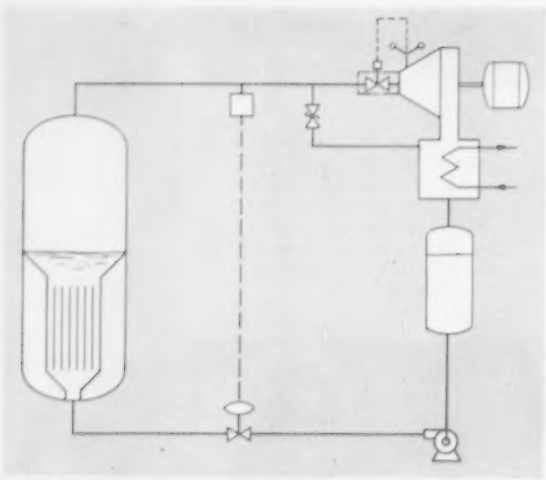

FIG. 3. Water-level control of feedwater flow

tend to affect this void volume in the wrong direction." While this statement is true, the important parameter is not vapor fraction but moderator density. It was pointed out in the article that although vapor fraction is affected by load changes in "the wrong direction," the moderator density is not necessarily affected in the same manner. The change in moderator density resulting from a change in load is determined by the power coefficient. This was discussed in connection with Fig. 4 of the article.

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**Hammond.** The three methods of control to be suggested here are certainly not claimed as "solutions" to the problem. They are not necessarily new, nor free from drawbacks, nor tested by response analysis. They are listed as examples of trying to solve the main problem of the boiling reactor, instead of doing major surgery on the basic advantages.

*Method 1. Move the control rod.* This original method of control (MacPhee's Scheme 2) may not be looked on with favor by those who insist that the reactor must be self-regulating, but it certainly meets the requirements of directness and simplicity. One drawback mentioned by MacPhee for this method is that it may be difficult to achieve rapid enough motion for control. However, the Borax experiment showed clearly that the reactor is self-regulating and self-protecting against very rapid changes in reactivity. The only destructive tendencies were those produced by repetitive pulsing (chugging) as the discharged fuel channels refilled with water. Thus the control system need not cope with nuclear transients, but only with hydraulic transients. But these can be regulated by design—baffling the return of discharged water or constricting slightly the inlet end of the fuel channels. The response time of the control system need not exceed a few tenths of a second.

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**MacPhee.** Although the early Borax experiments demonstrated self-regulating characteristics at *constant pressure*, later Borax experiments* demonstrated pressure and power instabilities due to load changes. The experiment in mind is sudden closure of the valve in the steam line with the reactor (Borax-3) operating at about 2 Mw and 130 psi. The resultant rate of pressure rise of ~1 psi/sec and equilibrium power of ~3.8 Mw was not alarming. However, the same characteristics in a reactor operating at say 60 Mw would be more troublesome since the larger ratio of power output to system heat capacity would produce a larger rate of pressure rise. Thus the so-called hydraulic transients cannot be dismissed briefly.

This is not to say that the above problem constitutes any great hazard since the installation of a relief valve will place an upper limit on any pressure and power rise. However, it is desired to prevent such an occurrence during normal operation.

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**Hammond.** The control rod should be driven by a signal derived from the external load in some way, instead of from a neutron-level signal (as distinguished from safety rods). One very convenient way of doing this is to use the steam-header pressure. Changes in steam demand are immediately reflected in the header pressure, and this source of information, coupled to the rod, would give the reactor a constant-pressure characteristic, which is most desirable. It appears that the rod motion could be actuated, if desired, entirely by hydraulic amplifiers (Fig. 1).

The other two methods operate on the alternative method of control—leave the rod setting constant, but adjust the effective void volume. In both cases this is accomplished by varying the water content of the core, or varying the thickness of the water reflector above the core.

It should be pointed out that the basic boiling reactor arrangement in MacPhee's Fig. 5 has one other control not shown. Engineers are reluctant to run boiler feed pumps in the vapor-bound condition, and a condensate receiver and a water-level control would certainly be added. The water-level control would throttle or bypass the feedwater flow. This apparently minor detail contains the possibility of control for the entire reactor, as shown in the following two methods.

*Method 2. Pressure-controlled feedwater throttle.* For this method (Fig. 2) the core arrangement approaches a once-through type boiler (the downcomers are minimized in volume), and the pressure in the steam header is used to throttle the feedwater flow. A drop in load gives a small increase in header pressure, which operates to reduce the

* J. R. Dietrich, H. V. Lichtenberger, W. H. Zinn, Design and operating experience of a prototype boiling water power reactor (U. N. Conference on Peaceful Uses of Atomic Energy, Geneva, 1955).

flow of relatively cool feedwater so that the average water temperature around the fuel plates increases. Also, the total water content of the core decreases, so that a drop in reactivity occurs until balanced by a lower steaming rate. The net effect is a redistribution of the void volume—first downward as the flow of cold water decreases, then upward as the reactor power drops. For very low loads there would be very little void within the core, and almost no water tamper above the core. At high steaming rates the core voids would be compensated by water tamping above the core and by hydrostatic head on the bubbles.

Adjustment of the water content of the core is more rapid if there is less water in the system; for this reason the reflector water is shown as isolated from the fuel channels. If the turbine stop valve closes, the water content of the reactor cannot decrease unless a relief valve to the condenser is provided. This valve can be smaller with a lower water content in the reactor. It is set above the normal operating pressure, and operates only if the turbine stop valve closes. External to the reactor, the only instrumentation change required is to actuate the feedwater throttle from a pressure signal instead of a water-level signal. A small bypassed feedwater flow is desirable to remove residual activity heat. This would conveniently be delivered through spray nozzles above the core so as to protect the upper end from the effects of momentary excess lowering of liquid level.

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**MacPhee.** In a boiling reactor employing natural circulation it is desirable to provide a chimney or riser above the core to increase power density. The presence of a riser section means that the water level in the reactor vessel will be several feet above the top of the core. This writer doubts that in such a reactor (using light water) allowable variations in water level (i.e., reflector thickness) will produce reactivity changes sufficiently large to compensate for the changes in vapor fraction.

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**Hammond.** *Method 3. Push-pull water-level control.** In this method (see Fig. 3), the water level of the outer reflector space is used to control feedwater flow by the usual method, but the core is shrouded and connected to the reflector space only at the bottom. At steady power rates the water levels in core and reflector are the same, but a sudden reduction in load would raise the pressure in the core region, forcing water out of the core to the reflector space. This increase in water level would actuate the pump throttle to reduce feedwater flow. The reverse would happen for a power increase. The connection at the bottom between the two regions would have to be small enough to provide damping of push-pull pulsations. A very small vent from the reflector vapor space to the condenser or steam header would be needed for purging. Because of gamma-ray and neutron heating of the reflector water, a portion of the feedwater should be injected into the reflector, so that it operates at the same temperature as the steam at normal power. If the change in heating effect of this region with power level is sufficient, it will act to raise and lower the water level in the core (since the control keeps the reflector level constant). If this change is insufficient, the short-term change of level will persist long enough (1–3 minutes) to allow a very slow or manual change in shim-rod position.

It is hoped that these discussions will stimulate those engaged in boiling reactor design to take an approach to the control problem that preserves the advantages of this useful reactor type.

* So named because of similarity to the Los Alamos Push-Pull reactor concept.

# Finding the Buckling of an Elliptic Cylinder

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*Hanford Atomic Products Operation*
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A reactor for propulsion of a ship or airplane might be mounted in a space where one horizontal dimension must be limited. Equations for such a reactor, one in the form of a right elliptic cylinder, can be solved using values given here.

The solution of the differential equation

$$\nabla^2\phi + B^2\phi = 0$$

is of wide interest in reactor theory. Solutions in rectangular, spherical, and circular cylindrical coordinate systems have achieved wide familiarity. It was established during development of wave mechanics that equations of this type can be separated and solved in a number of other orthogonal coordinate systems. There are, in fact, eleven such systems (*1*).

Attention here is directed to the solutions when the reactor is in the form of a right elliptic cylinder. The treatment is strictly applicable only to a bare reactor, but it may be extended to reflected reactors by the use of reflector savings in the way frequently employed for treating reactors of the three familiar shapes. Mathematically, our requirement then is that $\phi$ vanish on the surface of a right elliptic cylinder, and we desire the formula for computing $B^2$, commonly called the buckling, from the dimensions of the cylinder.

We use the notation: $L$ = length of the cylinder, $m$ = semi-minor axis, and $M$ = semi-major axis. Initially we select a rectangular coordinate system in which the $x$ axis lies along the major axis of the ellipse, the $y$ axis along the minor axis, and the $z$ axis along the cylinder axis, perpendicular to the elliptic cross section.

The dependence of $\phi$ upon $z$ can be factored out in the usual fashion. Its contribution to the buckling is given by $(\pi/L)^2$. Thus, if the origin of coordinates is at the center of the cylinder, we can write

$$\phi = \cos(\pi z/L) f(x,y)$$
$$B^2 = (\pi/L)^2 + B_0^2(m,M)$$

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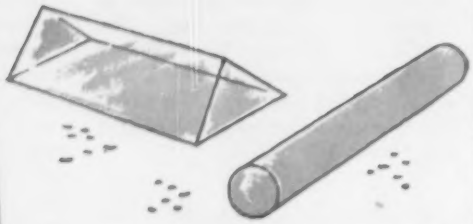

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reference to the dependence on $z$ and drop the subscript on $B_0^2$, designating it $B^2$.

To obtain the solution for $f$, we introduce the confocal elliptic coordinate system

$$x = A \cosh \xi \cos \eta,\ y = A \sinh \xi \sin \eta \tag{1}$$

By squaring and adding, these equations are shown to be equivalent to

$$(x^2/A^2 \cosh^2 \xi) + (y^2/A^2 \sinh^2 \xi) = 1 \tag{2}$$

Thus, the lines of constant $\xi$ are confocal ellipses with semi-major axis $A \cosh \xi$ and semi-minor axis $A \sinh \xi$. In particular, our elliptic cylinder will be bounded by some surface for which

$$\xi = \xi_0,\ M = A \cosh \xi_0,\ m = A \sinh \xi_0,\ c = M/m = \coth \xi_0 \tag{3}$$

where the ratio of the axes, $c$, is defined by the last equation. The differential equation in this coordinate system was first solved by Mathieu and the resulting functions bear his name (*2*). His paper is not now generally available and was not available to the authors. The same situation exists with Maclaurin's later paper (*3*). There is considerable later literature relating to this subject (*4*), but none is directly applicable to the calculation of $B^2$ from the dimensions of the ellipse. There is considerable variation of notation between various authors. We have adopted the notation of the Columbia tables (*4*).

In the elliptic coordinate system, the differential equation becomes

$$(\partial^2 f/\partial \xi^2) + (\partial^2 f/\partial \eta^2) + A^2B^2(\cosh^2 \xi - \cos^2 \eta)f = 0 \tag{4}$$

By the substitution $f = X(\xi)Y(\eta)$, this is separable into

$$(d^2Y/d\eta^2) + Y(b - A^2B^2 \cos^2 \eta) = 0 \tag{5}$$

and

$$(d^2X/d\xi^2) + X(A^2B^2 \cosh^2 \xi - b) = 0 \tag{6}$$

By the substitution $\cos^2 \eta = \frac{1}{2}(1 + \cos 2\eta)$ in Eq. 5 and $\theta = i\xi$ in Eq. 6, followed by a similar treatment of the $\cos^2 \theta$, these equations reduce to

$$(d^2Y/d\eta^2) + Y(a - \tfrac{1}{2}s \cos 2\eta) = 0 \tag{7}$$

$$(d^2X/d\theta^2) + X(a - \tfrac{1}{2}s \cos 2\theta) = 0 \tag{8}$$

where

$$s = A^2B^2,\ a = b - \tfrac{1}{2}A^2B^2 = b - \tfrac{1}{2}s \tag{9}$$

This substitution was made to reduce

the equations to the form given in the Columbia tables (*4*), which we shall use in obtaining the solution to the equations. Before proceeding to the solutions, expressions are obtained from Eqs. 5 and 3

$$B^2 = s(\cosh^2 \xi_0 - 1)/m^2, \text{ and}$$
$$c^2 = (1/\cosh^2 \xi_0 - 1) + 1 \quad (10)$$

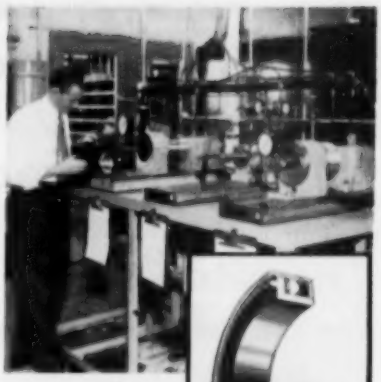
which we shall ultimately use to compute the desired $B^2$ in terms of the semi-minor axis $m$ and the ratio of the axes $c$. To anticipate, the result will be of the form

$$B^2 = K(c^2)/m^2 \quad (11)$$

which is quite analogous to the forms

TABLE 1—Values of cosh $\xi_0$, $c^2$, $c$, and $K$ for $s$ from 0–100

| $s$ | cosh $\xi_0$ | $c^2$ | $c$ | $K(c^2)$ | $5.7832\left(\frac{1+c^2}{2c^2}\right)$ | % error |
|---|---|---|---|---|---|---|
| 0.0 | — | 1.0000 | 1.0000 | 5.7832 | 5.7832 | 0.0000 |
| 0.2 | 5.4244 | 1.0352 | 1.0174 | 5.6849 | 5.6849 | 0.0010 |
| 0.4 | 3.8697 | 1.0716 | 1.0352 | 5.5898 | 5.5901 | 0.006 |
| 0.6 | 3.1881 | 1.1091 | 1.0531 | 5.4983 | | |
| 0.8 | 2.7861 | 1.1479 | 1.0714 | 5.4100 | | |
| 1.0 | 2.5149 | 1.1878 | 1.0899 | 5.3249 | 5.3260 | 0.021 |
| 1.2 | 2.3172 | 1.2289 | 1.1086 | 5.2431 | | |
| 1.4 | 2.1654 | 1.2711 | 1.1274 | 5.1642 | | |
| 1.6 | 2.0446 | 1.3144 | 1.1465 | 5.0886 | | |
| 1.8 | 1.9460 | 1.3588 | 1.1657 | 5.0162 | | |
| 2.0 | 1.8637 | 1.4043 | 1.1851 | 4.9469 | 4.9507 | 0.077 |
| 2.2 | 1.7939 | 1.4508 | 1.2045 | 4.8801 | | |
| 2.4 | 1.7340 | 1.4983 | 1.2241 | 4.8161 | | |
| 2.6 | 1.6819 | 1.5468 | 1.2437 | 4.7549 | | |
| 2.8 | 1.6362 | 1.5962 | 1.2634 | 4.6961 | | |
| 3.0 | 1.5958 | 1.6466 | 1.2832 | 4.6398 | 4.6477 | 0.170 |
| 3.2 | 1.5599 | 1.6978 | 1.3030 | 4.5860 | | |
| 3.4 | 1.5276 | 1.7498 | 1.3228 | 4.5344 | | |
| 3.6 | 1.4986 | 1.8027 | 1.3427 | 4.4851 | | |
| 3.8 | 1.4724 | 1.8563 | 1.3624 | 4.4378 | | |
| 4.0 | 1.4485 | 1.9107 | 1.3822 | 4.3925 | 4.4050 | 0.286 |
| 4.2 | 1.4267 | 1.9658 | 1.4021 | 4.3490 | | |
| 4.4 | 1.4068 | 2.0215 | 1.4217 | 4.3075 | | |
| 4.6 | 1.3884 | 2.0779 | 1.4415 | 4.2676 | | |
| 4.8 | 1.3715 | 2.1350 | 1.4612 | 4.2292 | | |
| 5.0 | 1.3559 | 2.1926 | 1.4808 | 4.1926 | 4.2104 | 0.425 |
| 5.2 | 1.3415 | 2.2507 | 1.5003 | 4.1576 | | |
| 5.4 | 1.3280 | 2.3094 | 1.5198 | 4.1239 | | |
| 5.6 | 1.3155 | 2.3687 | 1.5341 | 4.0915 | | |
| 5.8 | 1.3039 | 2.4285 | 1.5583 | 4.0603 | | |
| 6.0 | 1.2930 | 2.4887 | 1.5775 | 4.0303 | 4.0535 | 0.574 |
| 6.2 | 1.2828 | 2.5493 | 1.5968 | 4.0018 | | |
| 6.4 | 1.2732 | 2.6104 | 1.6157 | 3.9741 | | |
| 6.6 | 1.2642 | 2.6720 | 1.6345 | 3.9475 | | |
| 6.8 | 1.2557 | 2.7338 | 1.6534 | 3.9220 | | |
| 7.0 | 1.2477 | 2.7961 | 1.6722 | 3.8973 | 3.9258 | 0.73 |
| 7.2 | 1.2402 | 2.8587 | 1.6907 | 3.8737 | | |
| 7.4 | 1.2330 | 2.9218 | 1.7095 | 3.8507 | | |
| 7.6 | 1.2263 | 2.9852 | 1.7277 | 3.8284 | | |
| 7.8 | 1.2199 | 3.0486 | 1.7460 | 3.8074 | | |
| 8.0 | 1.2138 | 3.1126 | 1.7643 | 3.7869 | 3.8206 | 0.89 |
| 8.5 | 1.1999 | 3.2737 | 1.8094 | 3.7384 | | |
| 9.0 | 1.1876 | 3.4364 | 1.8538 | 3.6940 | 3.7331 | 1.06 |
| 9.5 | 1.1767 | 3.6007 | 1.8974 | 3.6528 | | |
| 10.0 | 1.1668 | 3.7661 | 1.9406 | 3.6152 | 3.6594 | 1.22 |
| 10.5 | 1.1580 | 3.9326 | 1.9831 | 3.5804 | | |
| 11.0 | 1.1502 | 4.0970 | 2.0241 | 3.5518 | | |
| 20.0 | 1.0771 | 7.2453 | 2.6917 | 3.2024 | 3.2907 | 2.76 |
| 25.0 | 1.0603 | 9.0489 | 3.0081 | 3.1059 | | |
| 40.0 | 1.0362 | 14.5781 | 3.8181 | 2.9459 | 3.0900 | 4.89 |
| 70.0 | 1.0199 | 25.9001 | 5.0892 | 2.8112 | | |
| 100.0 | 1.0138 | 37.1259 | 6.093 | 2.7681 | 2.9695 | 7.28 |
| ∞ | 1.0000 | ∞ | ∞ | 2.4674 | 2.8915 | 17.2 |

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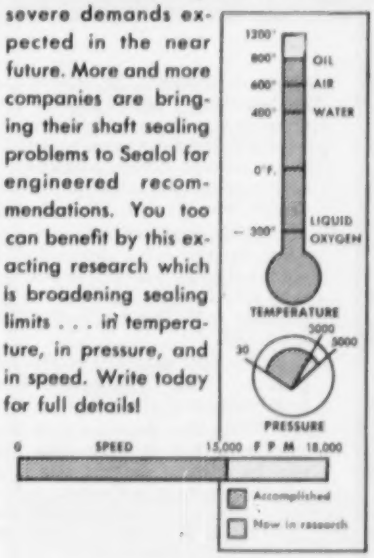


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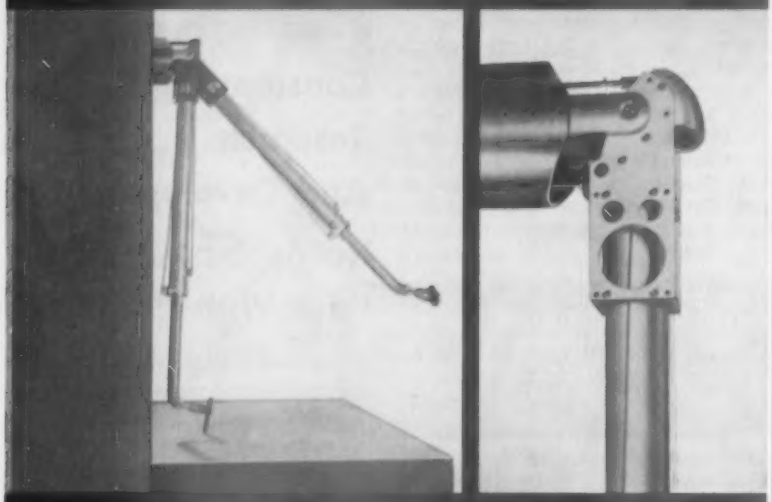

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in the simpler coordinate systems, e. g.,

$$B^2 = (2.4048)^2/R^2$$

in circular cylindrical geometry. In our case, $K(c^2)$ will have a different numerical value for each value of $c$. We shall expect in the limit $c = 1$ that $K(1) = (2.4048)^2$ since in that case the ellipse will reduce to a circle. Similarly, as $c$ approaches infinity the elliptic cylinder will approach an infinite slab of thickness $2m$, and we would expect the buckling to be $B^2 = (\pi/2m)^2$, or $K(\infty) = (\pi/2)^2$.

The solutions of Eqs. 7 and 8 have been obtained in various forms. Details are given in the bibliography in ref. *3*. For our purposes here the solution as it depends upon $\xi$ is most conveniently given in the form of an infinite series of Bessel functions

$$J_{e_0}(s,\xi) = \sqrt{\pi/2} \sum_{k=0}^{\infty} (-1)^k De_{2k}(s) J_{2k}(\sqrt{s} \cosh \xi) \quad (12)$$

where the $J_{2k}$ are Bessel functions and the coefficients $De_{2k}(s)$ are in ref. (*4*).

To use the solution, a particular value of $s$ is chosen and the coefficients $De_{2k}(s)$ are read from the tables. The series can then be constructed keeping the number of terms required to obtain the desired accuracy. The first root of this series then is determined numerically. That is, the lowest value cosh $\xi$ that makes $J_{e_0}$ vanish is designated cosh $\xi_0$. By using this value in Eqs. 10 we can obtain the value of $c^2$ corresponding to this case and also the numerator of $B^2$. By selecting another value of $s$, a second pair of values of $c^2$ and the numerator of $B^2$ can be obtained. Proceeding in this fashion a table of values for $c^2$ and the corresponding $K(c^2)$ is obtained. In Table 1 values are given for cosh $\xi_0$, $c^2$, $c$, and $K$ for selected values of $s$ from zero to 100, the highest value in the Columbia tables. The values were selected to give a detailed picture up to $c = 2$ and more widely spaced results for larger values of $c$. The values at infinity are obtained from the fact that in this limit the elliptic cylinder becomes a slab.

In Table 2, we have provided values of $c^2$ and $K(c^2)$ for more convenient values of $c$. Table 2 was obtained from Table 1 by interpolation in a manner explained in following paragraphs.

Imagine, for example, that it is required to locate a reactor in a space where one horizontal dimension must be limited. Perhaps this might occur in an aircraft or on board a ship. For

heat-transfer reasons, the reactor must be cylindrical. An elliptic cylinder will then give the best economy of fissionable material under these conditions. If the effective length and width of the reactor are each 2 meters, and buckling = $7.00 \times 10^{-4}$ cm$^{-2}$, then

$$B^2 = 7.00 \times 10^{-4} = [K(c^2)/(100)^2] + (\pi/200)^2$$

and $K(c^2) = 4.533$. By reference to Table 2, we find that the height must be 33% greater than the width or, in this case, 2.66 meters. To obtain the neutron distribution in this case would require using ref. (4). From our Table 1, the appropriate value of $s$ will be close to 3.4 and in construction of the solution as given by Eq. 12, the values of the $D$'s tabulated under this value of $s$ will be sufficient for most purposes.

In the last two columns of Table 1 are given values of a useful approximation to $K(c^2)$ and the error involved in using this approximation. The approximation is suggested by the fact that the buckling of a rectangle, where the ratio of length to width is $c$, can be obtained exactly by multiplying by $(1 + c^2)/2c^2$ the buckling of a square constructed on its short side. Here we have multiplied the buckling of a circle with radius equal to the minor axis of the ellipse by the same ratio. However, the approximation can be obtained in more logical fashion (5).

Because of the success of the approximation, we have assumed for interpolation purposes that $K(c^2)$ can lie represented over short intervals by an expression of the form

$$K(c^2) = h + g/c^2 \qquad (13)$$

This leads to an interpolation formula of the form

$$K(c^2) = K(c_2^2)\frac{c_2^2}{c^2}\left(\frac{c^2 - c_1^2}{c_2^2 - c_1^2}\right) + K(c_1^2)\frac{c_1^2}{c^2}\left(1 - \frac{c^2 - c_1^2}{c_2^2 - c_1^2}\right) \qquad (14)$$

where $c_1 < c < c_2$. This formula was used in the construction of Table 2 from Table 1.

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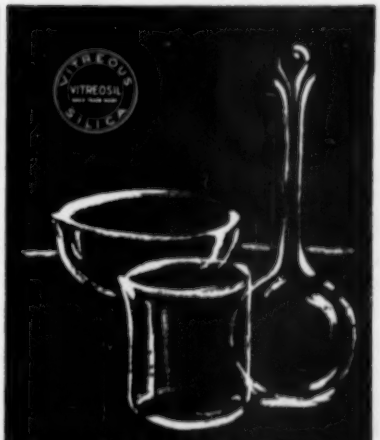
TABLE 2—Interpolated Values of $c^2$ and $K(c^2)$ for Convenient Values of $c$

| $c$ | $c^2$ | $K(c^2)$ | $c$ | $c^2$ | $K(c^2)$ |
|---|---|---|---|---|---|
| 1.00 | 1.0000 | 5.7832 | 1.40 | 1.9600 | 4.3534 |
| 1.01 | 1.0201 | 5.7262 | 1.42 | 2.0164 | 4.3112 |
| 1.02 | 1.0404 | 5.6708 | 1.44 | 2.0736 | 4.2706 |
| 1.03 | 1.0609 | 5.6170 | 1.46 | 2.1316 | 4.2314 |
| 1.04 | 1.0816 | 5.5647 | 1.48 | 2.1904 | 4.1939 |
| 1.05 | 1.1025 | 5.5140 | 1.50 | 2.2500 | 4.1580 |
| 1.06 | 1.1236 | 5.4646 | | | |
| 1.07 | 1.1449 | 5.4165 | 1.55 | 2.4025 | 4.0736 |
| 1.08 | 1.1664 | 5.3698 | 1.60 | 2.5600 | 3.9969 |
| 1.09 | 1.1881 | 5.3243 | 1.65 | 2.7225 | 3.9265 |
| 1.10 | 1.2100 | 5.2800 | 1.70 | 2.8900 | 3.8621 |
| | | | 1.75 | 3.0625 | 3.8029 |
| 1.12 | 1.2544 | 5.1948 | 1.80 | 3.2400 | 3.7481 |
| 1.14 | 1.2996 | 5.1139 | 1.85 | 3.4225 | 3.6976 |
| 1.16 | 1.3456 | 5.0372 | 1.90 | 3.6100 | 3.6506 |
| 1.18 | 1.3924 | 4.9646 | 1.95 | 3.8025 | 3.6073 |
| 1.20 | 1.4400 | 4.8952 | 2.00 | 4.0000 | 3.5684 |
| 1.22 | 1.4884 | 4.8292 | 2.50 | 6.2500 | 3.2748 |
| 1.24 | 1.5376 | 4.7662 | 3.00 | 9.0000 | 3.1080 |
| 1.26 | 1.5876 | 4.7061 | | | |
| 1.28 | 1.6384 | 4.6487 | 4.00 | 16.0000 | 2.9185 |
| 1.30 | 1.6900 | 4.5940 | 5.00 | 25.0000 | 2.8280 |
| 1.32 | 1.7424 | 4.5416 | 6.00 | 36.0000 | 2.7712 |
| 1.34 | 1.7956 | 4.4915 | | | |
| 1.36 | 1.8496 | 4.4435 | $\infty$ | $\infty$ | 2.4674 |
| 1.38 | 1.9044 | 4.3975 | | | |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# TECHNICAL ADVANCES

**Overseas Developments in Photomultipliers** A relatively small but interesting program of research and development in photomultipliers is underway in various laboratories in Europe. At the Scintillation Counter Symposium (p. 33) Dr. George Morton of RCA reported on their progress, based on a two-month trip to some twenty-five major European laboratories. Here is some of what Dr. Morton had to say.

**England.** Photomultipliers for scintillation counting are made under the direction of J. A. Lodge by the Electric and Musical Industries Laboratory at Hayes. Their present multipliers are based on the familiar venetian-blind structure, Fig. 1. These tubes have an end-on window with a semitransparent Cs-Sb cathode. They are made in a variety of sizes ranging from $\frac{3}{8}$ in. to about $4\frac{1}{2}$ in. and have 11–14 dynodes. Most of these tubes can be obtained with a photocathode with a lower limit of sensitivity of about 20 $\mu$a/lumen or in a slightly less sensitive version of the same multiplier with a sensitivity of about 10 $\mu$a/lumen. The gain is 0.1–5 $\times$ $10^6$ in the first class of multiplier and $\sim$20 $\times$ less in the second.

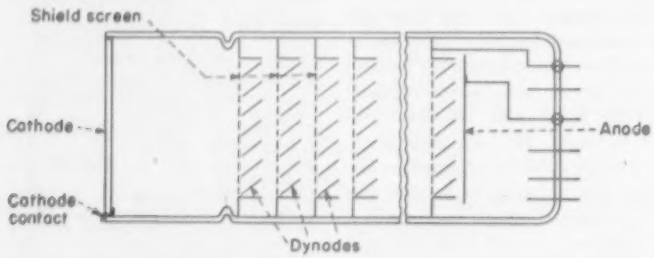


FIG. 1. EMI's venetian-blind tube

The EMI multipliers have very good collection of the electrons from the cathode. But the pulse-height statistics are somewhat impaired by the fact that apparently some electrons skip dynodes in the process of multiplication. The time characteristics of these multipliers are rather poor.

Ediswan Mazda also manufactures a line of photomultipliers (27M1, 27M2 and 27M3) that are similar to the RCA 931A. A new company is reportedly about to enter the multiplier field under contract to Harwell.

**France.** The Laboratoires d'Electronique et de Physique Appliquees, French subsidiary of the Philips Co., which is directed by Prof. Boutry, has a multiplier group headed by Dr. R. Champeix.

Work in this field started shortly after World War II. The first multiplier built by this firm used a linear structure that was set at an angle with respect to the cathode and axis of the tube. The design proved to be unduly large, awkward and difficult to shield and has been supplanted by two other types. One is a multiplier with a 50-mm (2-in.) diameter end-on cathode and a 10-stage linear multiplier structure following the Rajchman-Allen design. The cathode is activated with Cs-Sb and has a sensitivity of 40–50 $\mu$a/lumen. The dynode material used in the multiplier structure is Be-Cu from which they obtain a secondary-emission ratio of 3.5 at 180 volts per stage. The second type of multiplier has a 25-mm-diameter (1-in.) cathode and uses a semibox-type multiplier structure. This is also a 10-stage tube. The resolution obtained with these multipliers using $Cs^{137}$ and a NaI scintillator averages around 15% with a maximum of about 9%.

The Compagnie de Telegraphie Sans Fils has a small multiplier production unit at their research laboratory, which is located in a remodeled chateau at Puteaux some miles outside of Paris. The unit is under the direction of Dr. Dufour. Two types of multipliers are manufactured. One of these uses a venetian-blind structure. The second is somewhat similar to the DuMont design as far as its multiplier structure is concerned. These multipliers use an end-on semitransparent photocathode activated with Cs-Sb. Some of the cathodes are made on quartz so as to obtain ultraviolet sensitivity.

**Germany.** The Fernseh Company at Darmstadt has a small developmental group working on photomultipliers. They are producing just one, the FS-9, an end-on multiplier with a $\sim$25-mm-diameter cathode sensitized with Cs-Sb. The multiplier structure is rather complicated (Fig. 2). Dynodes are activated with

silver beryllium. The company is also making a few experimental photomultipliers on special orders. One such tube has a 4-cm cathode and a pinwheel type of dynode structure. With it they hope to get an output current of 200 ma.

Rather surprisingly, the great research laboratories at Eindhoven of the Philips Company are not working on the multiplier problem. The same is true of the Siemens Co., one of the largest electronic firms in Germany. No work is in progress in Siemens-Halske at Munich nor at the Siemens-Schuckert or Reiniger plants at Erlangen, Germany.

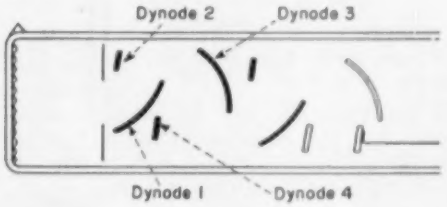


FIG. 2. Dynode arrangement used by Fernseh

**USSR.** During the Geneva Conference, Dr. V. Vavilov who has considerable familiarity with the situation with respect to photomultipliers in Russia, supplied some interesting information on the subject. According to Dr. Vavilov, four types of multipliers are being manufactured in a single large tube factory in Moscow. Cathode sizes are 125, 90, 50, and 30 mm. Some use a 10-stage structure and operate at 950 volts over-all while others employ 14 dynodes and operate at 1,500 volts. The multiplier structure is the same in all.

The photomultiplier displayed at the exhibit was a 14-stage linear multiplier having a 30-mm Cs-Sb photocathode. It was difficult to judge the dynode activation, but it was also probably a form of Cs-Sb. The last two dynodes differed from the others and possibly employed Cu-Be. The multiplier structure followed an early U. S. design, namely, the Rajchman-Allen type, quite similar to that used by Baumgarten in Zurich and others. The construction of this tube seemed to be fairly good, but its design far from optimum. The tube used a standard pin type base. The anode and photocathode were brought out separately from the base and had hand-cemented, machine-made grid caps as contacts. Inasmuch as the tube involved considerable hand work, production is probably small.

**University laboratories.** There are a number of university groups working on photomultipliers. At the Eidgenossische Technische Hochschule in Zurich, Dr. Baumgarten, who is in the department headed by Prof. Baumman, has a group that is continuing the multiplier work carried on for a number of years by Schaetti. This group is making two types of multipliers in fairly large numbers. These have end windows, 77 mm and 4 mm in diameter. They use a Rajchman-Allen type linear structure. To avoid feedback effects, the space between the structure and the glass window of the tube is partitioned off with perforated metal shields at intervals of about every fourth dynode.

This group is also constructing a number of large-area photomultipliers. These multipliers are built in viewing-tube bulbs with cathode diameters of 26 cm. The multiplier structures themselves are of the venetian blind type. See Fig. 3.

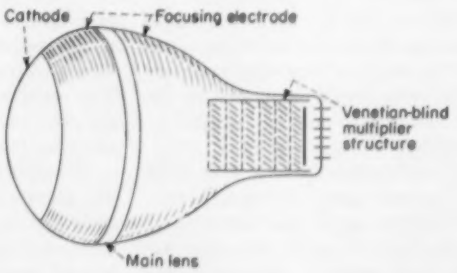


FIG. 3. Large (26-cm-diameter) photomultiplier from ETH, Zurich

At the Paris Observatory, Lallemand is building a few photomultipliers for astronomical purposes. These multipliers are very carefully hand-processed and have a very low dark current. Structures with 14 or more dynodes and opaque rather than semitransparent cathodes are used. Their performance as devices for measuring extremely low light levels has been quite outstanding.


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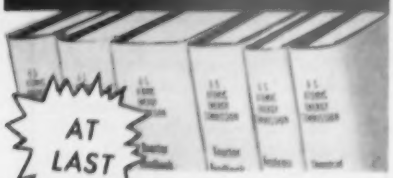


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# INDUSTRIAL APPLICATIONS

## Beta Gage Predicts Life of Filter Cloth

By J. J. BYRNES
*Walter Kidde Nuclear Laboratories, Inc. Garden City, N. Y.*

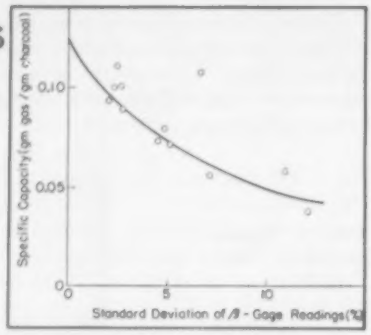
The beta-gage has now become standard for the measurement of weight per unit area or "thickness." Its wide acceptance is indicative of the unique solution that it offers for this problem and the efficacy of its performance. In the performance of a development contract for the Chemical Corps, we had occasion to construct a beta-gage for its usual application, but the information we obtained from it gave us an unexpected dividend. The scatter of the data turned out to be more closely correlated with filter-cloth life than the average value.

We were working on the design of a filter employing a filter cloth having combined gas adsorption and aerosol filtering properties. The ability of the cloth to adsorb gas comes from finely powdered charcoal dispersed in the matrix of fibers that forms the body of the cloth and does the aerosol filtering. The filter cloth was still under development and the material we were receiving for making prototype filters was variable in nature. To evaluate the worth of the filter design, it was essential to know what to expect from the filter cloth. Obviously, any test method would have to be nondestructive.

Our first thought was that the variation in gas life of the filter cloth could be correlated with the variations of total charcoal loading in the cloth. The beta-gage would give us the total weight per unit area, and since it was expected that the fiber weight content of the cloth would be constant, the charcoal loading could be obtained by difference.

We constructed the beta-gage using a $Sr^{90}$ source, an end window G-M tube for a detector, and a rate meter.

A calibration of the beta-gage was made. As expected, the unit was found to be capable of measuring the average weight per unit area to $\pm 2\%$. We then ran a series of tests in which we tried to correlate the average charcoal loading as determined by the beta-gage with the measured gas adsorption life. Much to our dismay the correlation was practically nonexistent.




**CORRELATION of filter-cloth gas-adsorbtive capacity with deviation of $\beta$-gage readings**

We then went back and studied the data more carefully. The sample sheets, which had been cut out of larger sheets, were 5 inches in diameter and the average weight per unit area of the charcoal in the sample had been determined by taking a series of nine readings over the area to be gas-tested. Each beta-gage reading covered an area 1 in. in diameter. In studying the data we noted that an increase in the scatter of the beta-gage readings generally indicated a poor gas life. We therefore calculated the standard deviation of the beta-gage readings taken for each test sheet and correlated these against its measured gas life. The resulting correlation, shown in the figure, permitted prediction of expected life of these test samples to $\pm 10\%$.

In the plot, the curve is extrapolated back to zero deviation, or the equivalent of a perfectly uniform sheet. This value should correspond to the total gas adsorptive capacity of the charcoal. We were able to check this intercept value by using multilayers of a very uniform cloth; the value obtained agreed closely with the value predicted from the extrapolated curve. The correlation was later used to predict the expected life of large filters and was found to apply equally well.

The apparent explanation for the usefulness of this correlation lies in the fact that the deviation in the beta-gage readings gave us a measure of the lack of uniformity of the sheet. The less uniform the sheet, the wider the variation in local flow velocity through the sheet, resulting in premature breakthrough at some point before most of the charcoal in the sheet had been used.

# BOOKS

## The Atomic Nucleus

By ROBLEY D. EVANS (McGraw-Hill Book Co., Inc., New York, 1955, xv + 972 pages, $14.50). Reviewed by ARTHUR ROBERTS, Department of Physics, University of Rochester, Rochester, New York.

This encyclopedic volume, which barely misses being 1,000 pages long, is the ultimate outgrowth of the notes from which Professor Evans has been teaching nuclear physics at MIT for the past twenty years. Having myself learned many of the elements of nuclear physics from the mountainous pile of hectographed pages from which the book evolved, I was curious to see how they have survived almost twenty years of evolution, and the final glorifying transfiguration to the printed page.

The contents show a difference in emphasis from that now customary. The book stresses a subject of special interest to the author, the loss of energy of radiation in matter, which gets eight chapters of detailed treatment (140 pages). There is a long chapter on radioactive series decay in the old pre-fission tradition, and three chapters on the statistics of random events, subjects rarely discussed in nuclear physics texts nowadays. Nuclear statics gets nine chapters (300 pages), the nuclear two-body problem one chapter (50 pages), and nuclear dynamics (mainly reactions) another 100 pages. There are 50 pages for alpha and beta decay. Not covered at all are experimental techniques, apparatus, or accelerators; high-energy physics and mesons rate a bare mention.

The characteristic feature of this book is what for want of a better term I must call self-sufficiency. It is a presentation of nuclear physics as one might give it for people who have had no advanced physics before and may never have a chance at it again.

Long as the book is, it is far from discursive; on the contrary, it is packed tight with information. Professor Evans is a hard man with facts; he collects them avidly, sustains and cherishes them, and is loath to let one go. Anything and everything necessary to explain a given nuclear phenomenon is included. Thus, chapter 2, on the radius of nuclei, after a short discussion of the ways in which the size of nuclei can be determined, suddenly branches off for thirty pages on an introduction to the wave properties of matter, which takes us all the way from de Broglie, via the detailed solution of the Schrödinger equation for the hydrogen atom, into a discussion of barrier penetration, and sets us down again, breathless, at a discussion of $\alpha$-decay.

Scattered through the book one can find a fair part of a course on modern physics, a goodish amount of probability theory, and a considerable fraction of an introduction to quantum mechanics. The result is a sort of obesity, a turgid overgrowth that conceals much excellent material. If ever a book could have profited by ruthless editing, this is it.

We have then, in the main, a treatment of classical nuclear physics that stresses the phenomenological aspect. It is a text one might well recommend to a student who for any reason must study the elements of nuclear physics by himself. The explanations are generally lucid and detailed.

Two other happy features of the book remain to be noted: a historical approach that has all but disappeared in recent years, and a remarkably wide selection of interesting and well chosen problems.

## Autoradiography in Biology and Medicine

By GEORGE A. BOYD (Academic Press, Inc., New York, 1955, xiii + 399 pages, $8.80). Reviewed by W. W. WAINRIGHT, School of Dentistry, University of Southern California, Los Angeles, California.

Dr. Boyd has not only done much of the work in the field of autoradiography but he now presents the most lucid book yet available on this complex subject.

Autoradiography is a very fascinating tool in biological and metallurgical research; it is to the biologist what the X-ray is to the clinician. With this tool one can visualize biochemistry in action.

Dr. Boyd has brought together the hard-to-find data derived from many fields of science. Detailed information is given on the characteristics of commercial and scientific photographic and specialty emulsions. Investigators in such varying fields as general photography and radioactive materials find in one book a summary of emulsions and their varying sensitivity to radiations of different types and energy.

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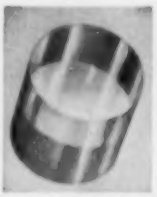

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to X-rays and gamma rays, for example, is in itself highly useful in industry as well as in biological and medical science. There are separate chapters on photographic materials for autoradiography, techniques of examining the autoradiographic image, factors affecting resolution, estimation of dose and exposure time, and, finally, a chapter considering sources of error.

The second part of the book is devoted entirely to the techniques of autoradiography. This section is equally amazing in the range of studies reported. For example, an entire chapter is devoted to techniques for nonflat surfaces, such as irregular objects and patients from the exterior. There are chapters on plant tissue, microscopic sections, smears, individual cells, dust and particulate matter. Still others consider fluids and the techniques for preparing histologic sections of undecalcified bones and teeth.

Dr. Boyd has studied the possibilities of beta-track autoradiography for many years and presents several examples pointing the way to future developments that will enable investigators to observe the location of single atoms within a cell. Dr. Boyd has applied all of the resources of the institutions with which he has been associated: the University of Rochester; the Institute of Nuclear Studies, Oak Ridge, Tennessee; the University of Tennessee; and the Arizona Research Laboratories of Phoenix, where he is now director.

Throughout the book all points are profusely illustrated with excellent graphs, tables and illustrations.

The final section of the book includes a comprehensive bibliography of approximately 750 references. The bibliography is cross indexed separately as to author and subject. There is a list of 12 books for supplemental reading.

## BOOKS RECEIVED

**Hochvakuum-Elektronenröhren—Band 1, Physikalische Grundlagen,** by H. Rothe and W. Kleen (Academic Press, Inc., New York, 1955, 297 pages, $8.33). The current volumes of this reference and text on electron tubes summarizes advances made since the 1940–41 edition. Volume 1 covers physical principles. Following volumes will discuss characteristics, application to the initial stages of the amplifier, and interference phenomena.

**The Theory of Hydrodynamic Stability,** by C. C. Lin (Cambridge Uni-

versity Press, New York, 1955, xi + 155 pages, $4.25). This book surveys the current understanding of the stability of steady fluid flow. Emphasis is on infinitesimal disturbances of a homogeneous viscous fluid.

**Electric Network Synthesis: Image Parameter Method,** by Myril B. Reed (Prentice-Hall, Inc., New York, 1955, x + 252 pages, $8.00). The image parameter method, presented in terms of image impedance function and image transfer function, is applied to combinations of two-terminal networks.

**Plane Waves and Spherical Means Applied to Partial Differential Equations,** by Fritz John (Interscience Publishers, Inc., New York, 1955, viii + 172 pages, $4.50). The author shows how a variety of results follow from elementary identities for plane and spherical integrals of an arbitrary function.

**Spheroidal Wave Functions,** by J. A. Stratton, L. J. Chu, P. M. Morse, J. D. C. Little, and F. J. Corbato (The Technology Press, Massachusetts Institute of Technology, and John Wiley and Sons, Inc., New York, 1956, xiii + 613 pages, $12.50). Certain forms of solutions and solutions are given for functions appropriate for prolate or oblate spheroidal boundaries. Tables provide values of solutions for certain variable ranges. All numbers were determined with the Whirlwind I digital computer.

**Generalized Thermodynamic Properties of Pure Fluids,** by A. L. Lydersen, R. A. Greenkorn, and O. A. Hougen (University of Wisconsin, Madison, 1955, $3.50). This book, report No. 4 of the University Engineering Experiment Station, presents thermodynamic properties for 59 organic compounds (hydrocarbons, ethers, esters, alcohols, sulfur and nitrogen compounds, organic halides) and 23 inorganic compounds. Tables and graphs cover ranges of reduced temperature and pressure for four parameters of the critical compressibility factor.

**Classics available.** Paperbound editions are available of: The Analytical Theory of Heat, by Joseph Fourier ($1.95); The Mathematical Analysis of Electrical and Optical Wave-Motion, by H. Bateman ($1.60); and Partial Differential Equations of Mathematical Physics, by A. G. Webster ($1.98). *Dover Publications, Inc., 1780 Broadway, New York 19, N. Y.*


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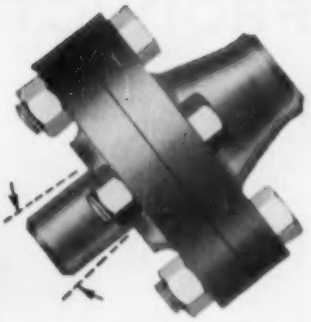

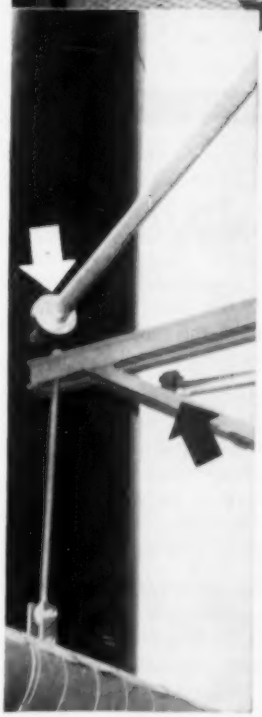

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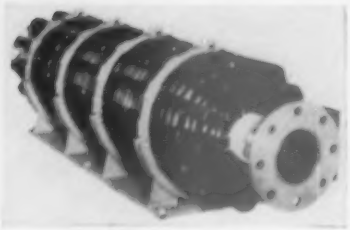
# PRODUCTS AND MATERIALS



### Electromagnetic Pumps

Several different types of pumps have been developed to handle the two classes of liquid metals used in nuclear applications. For bismuth, the d-c conduction pump, operating on same principle as electric motor, is used. A 100-hp pump requires 100,000 amperes at 2.5 volts and is about 40% efficient. The a-c conduction pumps are less efficient, particularly in the larger sizes. For sodium and similar metals, the induction pump, operating on the induction-motor principle, is used. Construction is virtually that of a standard polyphase stator with a fixed core and a large air gap through which is wound a pipe containing the metal. Spiral induction pumps are especially suited to low-flow, high-pressure applications; ratings of these pumps are 100 psi at 10 gpm, 80 psi at 40 gpm. Two forms of linear induction pumps are available, one the flat form with rectangular channel; the other with an annular channel.—British Thomson-Houston Co., Ltd., London, England.

### Portable Power Supplies

Portable high-voltage d-c power supplies provide up to 30 kv at 5 ma continuously. Ripple is <1%/ma at 30 kv; internal resistance 2.5 megohms.—Beta Electric Corp., 333 E. 103 St., New York 29, N. Y.

**Constant-current magnetic power supplies.** Using techniques ranging from chopper-stabilized thyratron control to dual-speed high-sensitivity electromechanical servo regulation, new magnetic power supplies provide long-term current stability better than 100 ppm; voltage ripple of less than 0.1% peak-to-peak; dynamic range from 15 to 100% of rated maximum current; and stepless continuous current control. Model shown is rated at 0–8 amperes over the load voltage of 0–2,500.—N J E Corp., 345 Carnegie Ave., Kenilworth, N. J.

## ELECTRONIC INSTRUMENTS AND APPARATUS

**Power supplies.** Series of power supplies has 50-kv isolation from ground on both sides of high-voltage circuit, so that several units can be operated in series. Supply is operable from 230-volt, 3-phase 60-cps power, exhibits < 1-volt peak-to-peak ripple at any output.—Levinthal Electronic Products, Inc., 2952 Fair Oaks Ave., Redwood City, Cal.

**Oscillator tubes.** New Type 6756 is a 3-electrode water-cooled tube with thoriated tungsten filament and 20-kw anode dissipation. Type 6757 is the equivalent forced-air-cooled tube with 15-kw plate dissipation. Both feature low mu, heavy-wall copper anode, and platinum-clad grid.—Amperex Electronic Corp., 230 Duffy Ave., Hicksville, N. Y.

**Voltage divider.** Miniature 3-section d-c voltage divider with 4 output terminals is available with a maximum of up to 1,000 ohms per section. Standard resistor accuracy is ±0.5%; wattage dissipation 0.5 w at room temperature, 0.25 w at 125° C.—The Daven Co., 530 W. Mt. Pleasant Ave., Route 10, Livingston, N. J.

**Delay line.** New device provides continuously variable delay from 0 to more than 1 μsec. Rise time is <8% of time delay at any point. Type 509 measures 1 × 6 × 6 in., weighs <14 oz.—Advance Electronics Co., Inc., 451 Highland Ave., Passaic, N. J.

**JAN shield insert.** JAN shield insert contacts bulb on one side, shield on other, conducting heat to shield with greater radiating surface and reducing bulb temperature by as much as 100° C.—Atlas E-E Corp., Bedford Airport, Bedford, Mass.

**Regulated d-c power rectifier.** New magnetic amplifier operates on 220/440 volts, 30, 50–60 cycles, and holds output voltage regulation from no load to full load within 0.5 volt, including variation of ±10% of rated input voltage.—Rapid Electric Co., 2881 Middletown Rd., Bronx 61, N. Y.

**Surface thermometer.** New spot-check surface thermometer has 50—1,000° F range, reaches stability within 60 sec.—Pacific Transducer Corp., 11863 W. Pico Boulevard, Los Angeles 64, Cal.

### Traveling-Wave CRT

High sensitivity CRT (above) photographically records transients in millimicrosecond region. High deflection sensitivity achieved by use of long traveling wave deflection plate system wherein signal velocity along plate is made equal to electron beam velocity, eliminating transit time distortion. Specifications follow: vertical (TW) sensibility, 0.02 volt/trace width; vertical (TW) sensitivity, 20 volts/in.; maximum vertical scan, 0.4 in.; horizontal sensibility, 0.17 volt/trace width; horizontal sensitivity, 170 volts/in.; horizontal scan, 0.5 in. Electron transit times: vertical (TW) plates, $0.2 \times 10^{-9}$ sec (per turn); horizontal plates, $0.35 \times 10^{-9}$ sec. Frequency response: vertical (TW) plates, 1,250 Mc 90% (3,250 Mc 50%); horizontal plates 720 Mc 90% (1,850 Mc 50%). TW helix impedance is 120 ohms each side to ground.—Edgerton, Germeshausen & Grier, Inc., 160 Brookline Ave., Boston 15, Mass.

**Pulse-forming unit.** This unit may be triggered at repetition rates up to 1 Mc; will produce either + or − pulses with 25-volt amplitude at 50 ohms, internal impedance with rise time of 0.02 μsec. It can generate pulses from 0.05–1,000 μsec pulse width with duty factors up to 25%.—Rutherford Electronics Co., 3707 S. Robertson Blvd., Culver City, Cal.

**Miniature multiconductor cable.** Miniature high temperature cables, jacketed and shielded, are available in single- to 24-conductor assemblies. Jackets can be Teflon, Kel-F, or glass fibre braid.—Hitemp Wires, Inc., 26 Windsor Ave., Mineola, N. Y.

**Subminiature reed relay.** A new resonant reed relay that functions simultaneously as audio frequency filter and relay, available in two- or three-reed design, provides automatic switching. Minimum driving voltage is 2½ volts (rms); reed frequencies can be tuned within range of 100–500 cps.—CG Electronic Corporation, Albuquerque, N. M.

**Multi-section potentiometer.** A single-turn precision potentiometer, available in five sizes, permits external independent phasing of each sectional cup without affecting phase relationships of others.—Clarostat Mfg. Co., Inc., Dover, N. H.

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**Silver cadmium cell.** Silcad battery uses silver cadmium couple. In a nominal 6 amp-hr cell, new couple has filled weight of 4.95 oz, volume of 5.05 in.$^3$, maximum of 1.25 volts, working voltage of 1.1.—Yardney Electric Corp., 44 Leonard St., New York, New York.

**Mercury battery.** Mercury batteries in standard miniature sizes can be stacked to provide required voltage in variety of shapes. Cell is 0.280 in. high, 0.490 in. in diameter.—P. R. Mallory & Co., Inc., Battery Division, North Tarrytown, N. Y.


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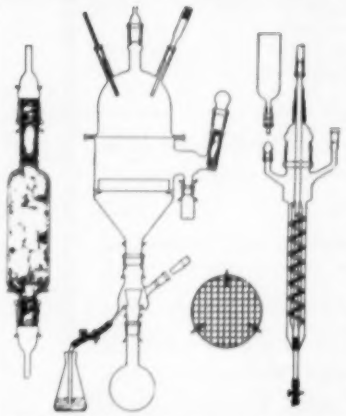

This all-glass cage system is used to study excretion pattern in urine, feces and expired air of rats injected with carbon-14 labeled compound. Ancillary equipment shown in diagram is also designed to work with cage systems for mice.

OPERATION: Column at left dries room air and frees it of $CO_2$. Center column houses the rats; air enters cage at top and is drawn off at bottom. Column at right absorbs $CO_2$ from rat chamber which may be recovered for radioassay.

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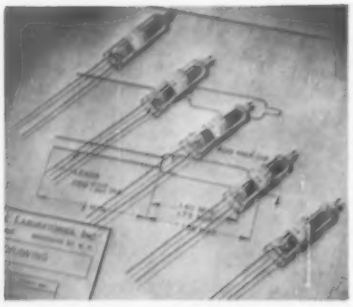

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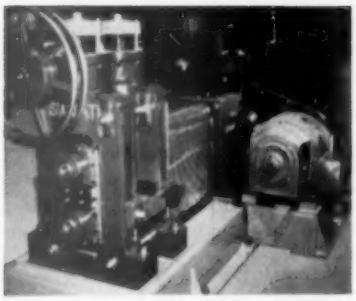
Linear amplifier for use with counters has regulated HV supply and provision for operating external cathode follower; built-in metered voltage discriminator. Gain is 100–10,000 in 2-db steps. Independently selectable rise and fall time constants: 0.03–10 microseconds and 0.1–100 microseconds. Dual purpose quench/amplifier is also available.—Isotope Developments Ltd., Beenham Grange, Aldermaster Wharf, Near Reading, Berks, England.

**Oscilloscope.** Type 310 is a d-c-to-4-Mc portable oscilloscope with wide-range sweep circuit of 0.5 μsec/div to 0.6 sec/div continuously variable with 18 calibrated steps from 0.5 μsec/div to 0.2 sec/div, accuracy within 3%, 5× magnifier.—Tektronix, Inc., Portland 7, Ore.

**Vari-count.** New Vari-count, soon available, has input requirement of 0.1 μsec triggering amplitude +15 volts, a positive edge having rise times of at least 40 v/μsec. Input impedance is 56 μμf in series with 1,000 ohms. Other technical data—output: (a) Each useful position has isolated pentode output capable of developing a negative 35-volt d-c pulse across 6,800 ohms, (b) Positive 50-volt pulse occurs at the $n$th count which is associated with zero setting the MBS tube (exception when $n$ equals zero); scaling: units may be cascaded directly; repetition rate: random to 100 kc for counts less than 10, random to 800 kc for 10-count or decade scaling; resolution time: (a) "$n$" position counter: ~0.1 μsec for 0,1,2,3—$(n-1)$ positions; less than 6 μsec for $n$th position; (b) decade counter: ~0.1 μsec for all positions.—Haydu Brothers of N. J., Plainfield, N. J.

**Tantalum capacitor.** Type STA, a solid tantalum capacitor using no liquid or paste electrolyte, operates well at −70—+85° C.—Fansteel Metallurgical Corp., North Chicago, Ill.

## LABORATORY INSTRUMENTS AND APPARATUS



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*Request Bulletin 314*

2

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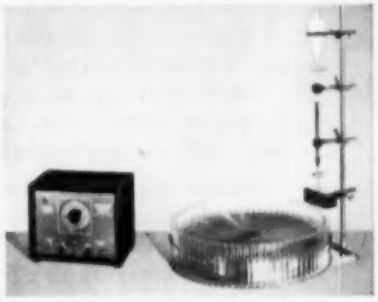

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3

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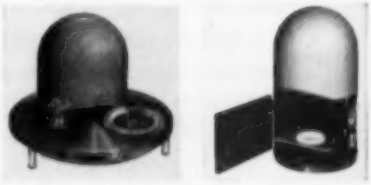

Both types can be used for Geiger and proportional operation.

Windowless Flow Counter, Model 200A, provides maximum sensitivity for counting solid samples which emit very soft radiations. Has essentially unlimited life. Physical arrangement of sample in chamber makes it possible to achieve full $2\pi$ geometry.

Flo-Window Counter, Model 210, features a very thin metalized window of Du Pont Mylar which offers a minimum of obstruction to low energy radiation. Isolates counting chamber from sample. Eliminates static charge, vapor effects, accidental contamination, etc.

*Request Bulletin 200*

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**Kel-F coatings.** Kel-F Dispersions, consisting of 1-20-micron particles suspended in volatile organic liquids, provides tough, adherent coating for metals, nonmetallic materials. May be sprayed, dipped, or spread.—M. W. Kellogg Co., Jersey City 3, N. J.

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**Electron diffractograph.** Swiss instrument allows every method of electron diffraction. The beam is accelerated through a variable potential of 20 to 50 kv, with anode diaphragm in a self-centering cone. Beam diameter is less than 10 microns, permits optical line width of more than 100 microns.—Trüb, Täuber & Co. AG., Zurich, Switzerland.

**Foam-in-place powder.** New plastic powder cures to a low density foam that can be used up to 175° C. At 20-lbs/ft³ density, dielectric constant at $10^{10}$ cps is 1.48, dissipation factor 0.009. Compressive strength is 600 psi.—Emerson & Cuming, Inc., 869 Washington St., Canton, Mass.

**Microcard reader.** Pocket size Microcard reader weighs 7 ounces, has wide-field 12× lens, operates on batteries or on 110 volts.—Microcard Foundation, Box 2145, Madison, Wis.

**Gear reduction transmission.** New transmission gives infinitely variable gear reduction from true zero to 80 rpm, with 1,750 rpm input speed, and develops 100 in.-lb torque.—Revco, Inc., 711 W. Lake St., Minneapolis 8, Minn.

**Security bars.** Security bar set for file cabinets consists of rigid steel channel, notch pin for bottom section of file, clevis pin for top section. Bars are available in various lengths; installation is simple.—Reed Manufacturing Co., 1045 Main St., Waltham 54, Mass.

**Ionization gage control circuit.** New instrument, which measures pressures from 1 micron to $2 \times 10^{-10}$ mm Hg, has ion-current amplifier employing 100% negative feedback.—Vacuum Electronic Engineering Co., 86 Denton Ave., New Hyde Park, N. Y.

**Filters.** New filter of porous stainless steel filter in temperatures up to 1,200° F, differential pressures of 2,000 psi. Poro-Klean has tensile strength of 9,000–25,000 psi; percent of elongation of 3–6%; porosity of 30–50%. Retains 3–30-micron particles.—Cuno Engineering Corp., Meriden, Conn.

## LITERATURE AVAILABLE

**Irradiation of solids.** "Effect of Irradiation on Solid Materials" is a bibliography containing more than 300 titles.—Penn-Texas Corp., 730 Fifth Ave., New York 22, N. Y.

**Induction heating.** Bulletin 1500 describes remote heating station used with induction heating equipment of 960, 3,000, or 9,600 cycles and with power output from 30 kw to 300 kw. Heating control station is covered in Bulletin 1490.—High Frequency Heating Div., Lindberg Engineering Co., 2444 W. Hubbard St., Chicago 12, Ill.

**Synthetic fluids and lubricants.** New booklet describes polyalkylene-glycol-type fluids and lubricants. 52 p.—Carbide and Carbon Chemicals Co.,


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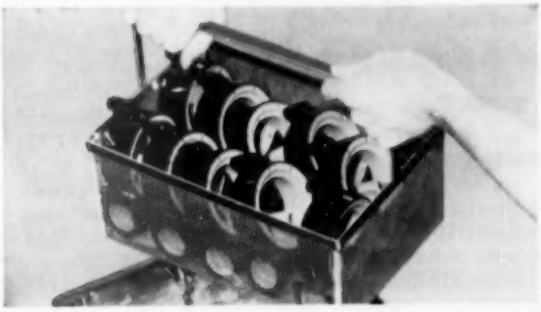

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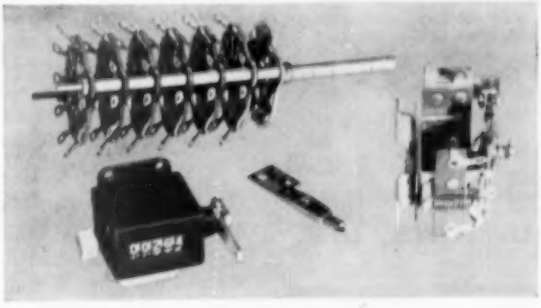

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Div. of Union Carbide and Carbon Corp., 30 E. 42 St., New York 17, N. Y.

**Contact modulators.** New bulletin describes their theory and application. 16 p.—Airpax Products Co., Middle River, Baltimore 20, Md.

**Deflection indicator.** Magnetic-amplifier type deflection indicator is described in bulletin 05B8385. 8 p.—Allis-Chalmers Manufacturing Co., 1316 S. 70 St., Milwaukee, Wis.

**Vibrating-reed electrometer.** Models 30 and 31 Cary Vibrating Reed Electrometer are fully described in new bulletin.—Applied Physics Corp., 362 W. Colorado St., Pasadena, Cal.

**Pressure gage.** High-temperature pressure gage giving accurate readings under prolonged exposure to high temperature and radiation is described in 4-page brochure.—Gallery Chemical Co., 201 N. Braddock Ave., Pittsburgh 8, Pa.

**Voltage-digital translators.** Article outlines theory and applications of high-speed voltage-to-digital translators. 8 p.—EPSCO, Inc., 588 Commonwealth Ave., Boston, Mass.

**High-temperature terminals.** Bulletin supplies data on new high temperature hermetic terminals. 2 p.—American Lava Corp., Chattanooga 5, Tenn.

**Spectrographic supplies.** Catalog-price list covers special pure materials and alloy standards; plates and films; graphite electrodes and powders; other spectrographic supplies. 24 p.—Jarrell-Ash Co., 26 Farwell St., Newtonville, Mass.

**Sealless centrifugal pumps.** Bulletin 1020 gives full information on Series DE (Double Ended) Chempumps. 4 p.—Chempump Corp., 1300 E. Mermaid Lane, Philadelphia 18, Pa.

**Ceramic transducers.** Applications, properties, and specifications for piezoelectric ceramic transducers are covered in brochure. 12 p.—Gulton Industries, Inc., Metuchen, N. J.

**Proportional counting systems.** Six types of proportional counting systems for measuring radiation are compared on 13-points. 2 p.—Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis 18, Ind.

**Lithium hydroxide.** Full data on Trona lithium hydroxide is given in folder which also gives information on the manufacturing plant.—American Potash & Chemical Corp., 3030 W. Sixth St., Los Angeles 54, Cal.

**Continuous-cast bearing bronze (SAE 660).** Bulletin gives full information on Asarcon 773 bearing bronze. 6 p.—American Smelting and Refining Co., Barber, N. J.

**Spherical union connection.** Data sheet describes features and uses of Jerguson union connection. 2 p.—Jerguson Gage & Valve Co., 80 Fellsway, Sommerville 45, Mass.

**Rotary switches.** Application, operation, and specifications of rotary control and instrument switches are covered in new bulletin. 8 p.—Allis-Chalmers Manufacturing Co., S. 70 St., Milwaukee, Wis.

**Computing and data reduction facility.** The facilities and scope of new service group are described in Bulletin R-16.—Cook Electric Co., 2700 Southport Ave., Chicago, Ill.

**Gear box.** A new catalog sheet gives full data on gear boxes for use in actuators, computers and small electronic components.—Southwestern Industries, Inc., 5880 Cantinela Ave., Los Angeles 45, Cal.

**Diallyl phthalate prepolymer.** Applications and basic data on Dapon resin, a thermoplastic powder soluble in low molecular weight ketones, benzene, etc., and used in molding compositions, resin blends, and laminates, are given in new booklet. 6 p.—Ohio-Apex Div., Food Machinery & Chemical Corp., Nitro, W. V.

**Tape-to-card converter.** Catalog sheet describes automatic tape-to-card converter for use with 024 or 026 IBM key punches.—Systematics Inc., 30 Hermosa Ave., Hermosa Beach, Cal.

**Potentiometer-type voltage divider.** Vernistat, a 400-cycle a-c potentiometer, is described in brochure. 4 p.—Perkin-Elmer Corp., Norwalk, Conn.

**Electronic equipment.** Equipment and components used in electrical and electronic industries are described in brochure. 4 p.—Mico Instrument Co., 80 Trowbridge St., Cambridge 38, Mass.

**Recording equipment.** Type 6 FM-Carrier recording system is described in pamphlet. 4 p.—A-V Manufacturing Corp., 730 Fifth Ave., New York 19, N. Y.

**Ceramic capacitors.** Standard ceramic capacitors are described in catalog. 20 p.—Cornell-Dubilier Electric Corp., South Plainfield, N. J.

**Phototubes.** Catalog describes 45 types of phototubes. 24 p.—Radio Corp. of America, Tube Division, Harrison, N. J.

**Replacement tubes.** "Interchangeability Directory" lists 2,000 tubes with RCA direct replacement type or equivalent. 16 p.—Radio Corporation of America, Tube Div., Harrison, N. J.

**Nuclear equipment.** Nuclear instruments, including medical spectrometer and focusing collimator, are described in catalog.—Detectolab, Affiliate of Borg-Warner Corp., 6544 North Sheridan Rd., Chicago 26, Ill.

**Fatty alcohols.** New booklet describes large line of straight chain aliphatic alcohols. 12 p.—M. Michel and Co., 90 Broad St., New York 4, N. Y.

**Counter converter.** Self-powered unit that converts any scaler for proportional-counter output is described in bulletin. 4 p.—Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis 18, Ind.

## Applying Radiation to Industry

That's the subject of a case-study special report scheduled for the May issue of NUCLEONICS. It will cover uses in both industrial research and production processes under the headings:

- Research
- Industrial tracing
- Hydraulics
- Wear studies
- Isotope dilution and tracer analysis
- Activation analysis
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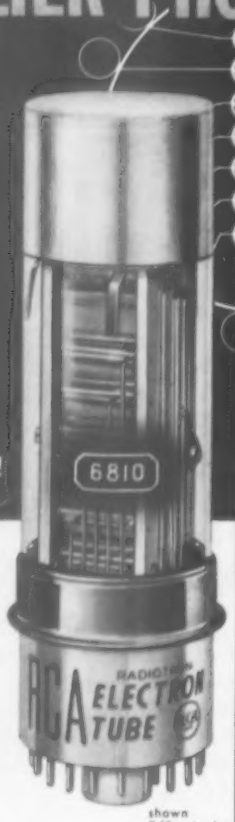


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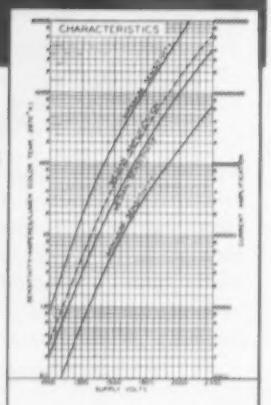


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## Tracers Locate Entrainment

(*Continued from p. 83*)

sponded to over-all entrainments of only 0.02–0.08% of the pitch, which are only a fraction of the values obtained by analysis for trace metals in both distillate and feed. Since the metals and radioactivity analyses of the runback fluid agree, and since other considerations indicate the metals analyses are reliable indices of over-all entrainment, it is concluded that the radioactive compound was selectively removed to some extent in the distillate stream. This conclusion is reached in spite of the result of the special test, which indicated adsorption was not a problem. The very large area of the condensers in this system may be responsible; the area is so large that all of the radioactive compound believed to be in the distillate from a single run (~160 mg) could adsorb as a monolayer on only 10–20% of the surface.

After some of the pilot runs it was discovered that significant fractions of the activity were retained in the injection vessels in spite of the heating and the use of flushing liquid. Thus, in four of the tests the fraction injected was determined by measuring the radiation intensity before and after injection. The amount charged was known, so that the material balances shown in Table 1 could be calculated. The yield was 82–120%, with the exception of the 140% yield for the transfer line injection. These deviations from 100% do not affect the conclusions with respect to degree of entrainment. Variations of activity with time for three of the experiments are shown in Figs. 4–6.

**Safety.** When tracer is injected into the oil stream, great dilution effectively removes any hazard except possible precipitation or reconcentration of the isotope. This possibility was studied with respect to "coking out" of isotope from pitch that was used as feed for a thermal cracker. Activity balance in inlet and outlet of this unit was determined, and activity loss was insignificant despite 900° F temperature.

*The authors acknowledge the contributions of many members of the Shell research and refinery staffs. Special acknowledgment is due to H. D. Evans, who proposed the entrainment tests and aided in their planning, F. A. Cleland, who analyzed a large part of the data, and to E. J. Hall, R. A. Mugele, and D. Y. Schumacher, all of Shell Development Company; C. B. Coenen of Shell Oil Company, and B. Carrigan of Shell Oil Company, Canada, Ltd.*

### BIBLIOGRAPHY

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# LETTERS

## Neutron-Facility Calibration

DEAR SIR:

In connection with the article "Calibrating a Neutron Facility for Biological Research," by Curtis *et al.* (NU, Feb. '56, p. 26), I would like to present some experimental data that I obtained with this facility.

At the time that I was working on a thesis problem with this facility, it was known that a given gold foil would be activated to the same extent in a given time regardless of its plane of orientation in the column. Therefore it was believed that the thermal-neutron flux in the column was isotropic. This belief was held in spite of the fact that, as the article states, "the flux is essentially uniform across any horizontal plane in the exposure cavity but varies in a vertical direction."

To test whether the flux was isotropic or not, I took a $\frac{1}{2}$-in. cube of Lucite, glued a piece of cadmium metal to each face, and placed a gold foil on the outer surface of each piece of cadmium. The cube was then suspended in the center of a Lucite exposure box and irradiated in the column.

The results of the foil counting showed a flux ratio between the top, any side, and the bottom of 0.6/0.8/1. From these results, I concluded that the thermal-neutron flux is not the same from all directions at a given point in the exposure cavity and therefore it is not isotropic.

From the information concerning the flux distribution in the column and from the fact that the facility is located above the reactor, one could state that in spite of being thermalized the net movement of neutrons is into the exposure cavity from the reactor face and out the other five sides of the cavity.

—LIONEL LEWIS
*Nuclear Laboratory*
*The Glenn L. Martin Company*
*Baltimore, Maryland*

## Training U. K. Nuclear Engineers

DEAR SIR:

After reading in the "Roundup" section of the December NUCLEONICS (p. 14) about the shortage of British nuclear engineers, it seemed to me that your readers might be interested in an account of the steps being taken to alleviate the situation.

Until comparatively recently, all research on and development of nuclear energy in the United Kingdom has been carried out by the government-sponsored U. K. Atomic Energy Authority. Correspondingly, the teaching of nuclear engineering has been confined almost entirely to Harwell.

When private industry first entered the nuclear energy field, staff was drawn either from the AEA, or industrial personnel were sent for training to Harwell and/or one of the other AEA establishments. Now, however, the universities are commencing to offer both undergraduate and postgraduate courses to supply the nuclear engineers who are so badly needed.

The Harwell Reactor School is still the only place in Britain at which students can actually use and work with reactors. Here a 12-week course includes 150 hours of lectures, time for discussion, and experimental work. Much of this experimental time is spent with a "reactor simulator" to give students the feel of handling a reactor without any risk or any using of reactor time.

A somewhat similar intensive course for postgraduate students has been organized by the University of Manchester, the lectures being mainly given by AEA personnel. It is expected that in future years the lecturing staff for this course will be drawn more from the engineering and physics departments of Manchester University.

On the undergraduate level, Queen Mary College, one of the colleges that make up the University of London, has been giving a course in nuclear engineering for the last four years. Glasgow University started a similar course in the current session, and at the present time Imperial College at London, the Royal Technical College in Glasgow, and the University of Birmingham are advertising for staff for courses in nuclear engineering that they propose to set up. There is no doubt that other universities will be following the lead.

At both Queen Mary College and at Glasgow the course is intended primarily for engineering students in their final year. These students have all had elementary physics at some stage in their career, but have little or no knowledge of nuclear physics.

At Glasgow the lecture course consists of 40-hour periods, of which the first 30 are given by the physics department of the university and the last 10 by the engineering department. In the


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# BASIC RESEARCH at los alamos

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first 30 lectures, basic nuclear physics occupies 10 hours, and the physics of reactors an equal period. In the third group of 10 lectures such subjects as health physics, shielding, and breeding are discussed. The engineering part of the course is concerned with the transfer of heat from reactors and its conversion to useful power.

Although no reactors or even exponential piles are as yet available for universities in Britain, experiments of slowing-down lengths of neutrons are carried out in the Glasgow laboratory course using an Sb-Be source that gives about $10^6$ 35-kev neutrons per second. This source is also used for thermal and fast-neutron-capture- cross-section measurements. Other neutron experiments, such as one on the elastic collisions of neutrons and protons using a plastic scintillator as the source and detector of knock-on protons, are carried out using a weak Po-Be source. In addition there are standard nuclear physics experiments on absorption, radioactivity, etc., specially chosen from the normal physics course for their applicability to nuclear engineering. A similar laboratory course is run at Queen Mary College.

At the present time the course in Glasgow is experimental, in the sense that in the light of experience changes will be made. For example, it is hoped to extend the course to cover metallurgical problems more fully, and to increase the time spent on reactor theory.

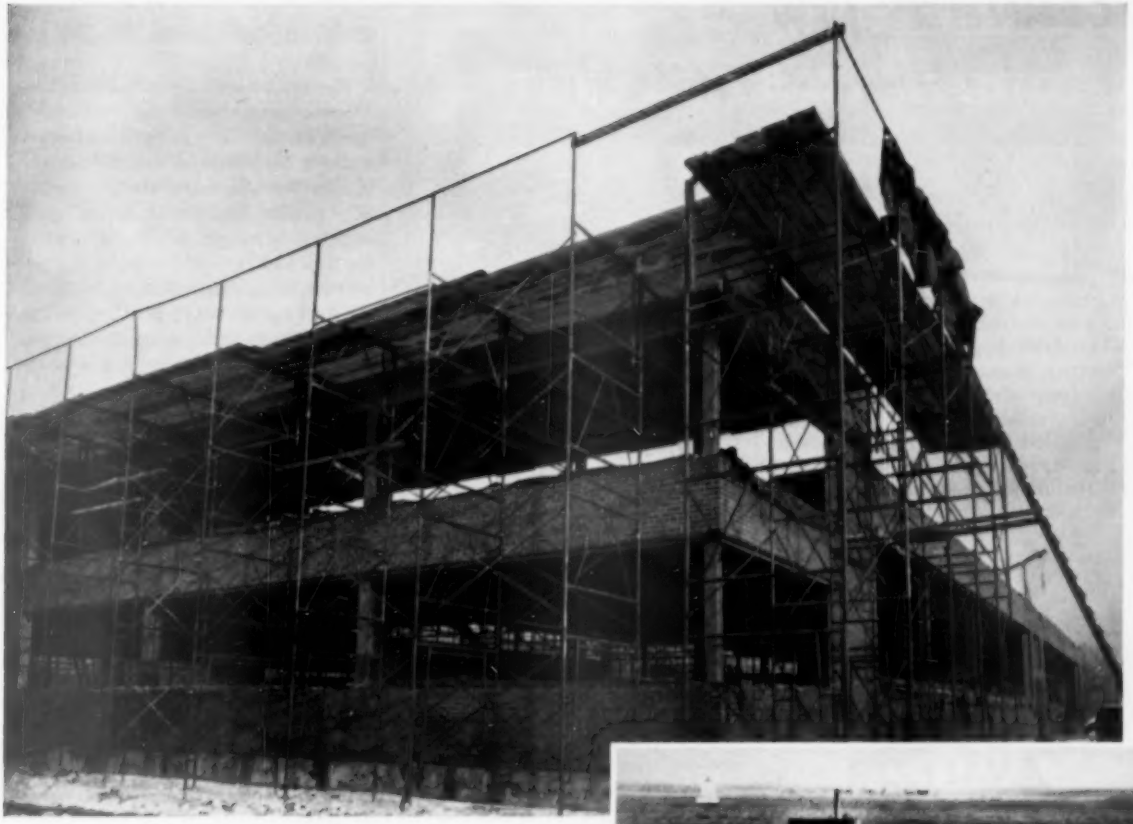

—K. G. McNeill
*Department of Natural Philosophy*
*The University*
*Glasgow, Scotland*


## Graduate Program at University of California

Dear Sir:

The February Nucleonics described some of the university courses in nuclear engineering. I noted with some dismay that no mention was made of our Master and Ph.D. programs in nuclear engineering, which were initiated last fall by the Mechanical Engineering Division at Berkeley.

The Master of Science program consists of the following courses: advanced applied mathematics, nuclear reactor physics, elements of heat and mass transfer, power cycles and power-plant systems, nuclear reactor kinetics, automatic control of nuclear reactors, process heat and mass transfer in nuclear engineering, reactor materials, design of reactor-power-plant systems, semi-



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Further information may be obtained by writing to the Dean of Engineering, University of California, Berkeley. The deadline on applications for admission is July 15.


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# NEWSMAKERS

**Edward L. Heller,** staff engineer for the Joint Congressional Committee on Atomic Energy, heads up a new, separate group within the H. K. Ferguson Co. to supervise design and construction projects in atomic energy. The new group will be located in Cleveland.

**Lloyd R. McIntosh,** head of the production division at High Voltage Engineering Corp. since 1950, has been appointed general manager.

Armour Research Foundation has promoted **Richard F. Humphreys,** manager of its physics research department and initiator of its nuclear reactor program, to the new position of assistant director for technical development.

**Karl P. Cohen,** founder and former vice-president of Walter Kidde Nuclear Laboratories, has been named a consulting engineer in General Electric's Atomic Power Equipment Department.

**Cramer W. LaPierre,** General Electric vice-president, has been elected an executive vice-president of the company, with over-all responsibility for the atomic, electronic and defense systems group.

Walter Kidde Nuclear Laboratories has elected **Wilbur E. Kelley** as president, succeeding **Henry K. Norton** who continues as a director of the atomic research, development and engineering firm. Kelley, former manager of the New York Operations Office of AEC, had been vice-president, engineering, for Catalytic Construction Co. of Philadelphia since 1953.

**C. D. W. Thornton** has been appointed head of atomic energy activities for Farnsworth Electronics Co. of Fort Wayne, Ind., a division of I.T. & T. He had been director of operations analysis and planning at AEC.

**Louis Ten Eyck Thompson,** director of research at Norden-Ketay, has been elected vice-president for research.

**William Shockley,** inventor of the junction transistor, heads the new Shockley Semiconductor Laboratory established by Beckman Instruments Inc. The new lab, to be completed in August at Stanford Industrial Park, Palo Alto, Calif., will develop transistors and other semiconductor devices.


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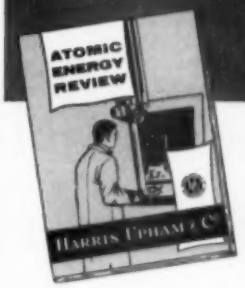
On Peace-Time Atomic Energy

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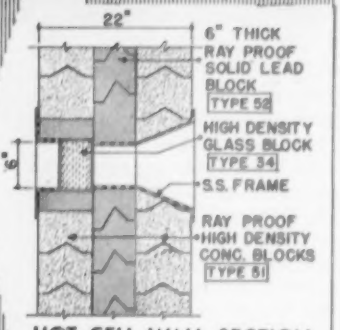


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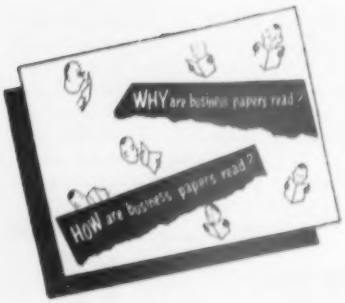


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## NUCLEAR CALENDAR

**April 16–18**—First annual conference and exhibit of ASME Gas Turbine Power Division, Washington (*Statler*). Session on nuclear power and closed cycles, 18th afternoon. Contact ASME, 29 W 39, NYC 18.

**April 17–18**—Regional conference, (Atomic Industrial Forum), Atlanta, Ga. (*Biltmore*). On 19th the conference moves to Oak Ridge to visit research and production facilities. Contact D. J. Scherer, AIF, 260 Madison Ave., NYC 16.

**April 25**—Symposium on Ceramics for Atomic Energy (American Ceramic Society), New York (*Statler*). Fourteen papers on theory, preparation and application of ceramics. Contact ACS, 4055 No. High St., Columbus, O.

**May 9**—Nuclear Energy Writers Assn., annual meeting, New York. Contact sec'y. Gordon Molesworth, 260 Madison Ave., NYC 16.

**May 10–11**—Regional meeting, Atoms in Business (Atomic Industrial Forum), San Antonio, Tex. (*Plaza*). Applications, opportunities, effect on the Southwest. Contact AIF (see above).

**May 14–16**—Conference on Basic Mechanisms in Radiobiology (National Research Council), Highland Park, Ill.

**May 15–16**—Industrial Nuclear Technology Conference (co-sponsored by Armour Research Foundation and NUCLEONICS). The uses of radioactivity in industry and research. Contact John Forewalter, ARF, 55 E 33, Chicago, or NU, 330 W 42, NYC 36.

**May 17–19**—Annual meeting, Radiation Research Society, Chicago (*Palmer House*). Contact H. S. Kaplan, Radiobiology Dept., Stanford University Hospitals, San Francisco 15.

**June 6–8**—American Nuclear Society, 2d annual meeting, Chicago (*Palmer House*). Contact Exec. Secy. ANS, Box 963, Oak Ridge, Tenn.

**June 16–23**—Fifth World Power Conference, Vienna. Development of power production and utilization, waste purification, international collaboration. Contact Engineers' Joint Council, 33 W 39, NYC 18.

**June 21–23**—Society of Nuclear Medicine, annual meeting, Salt Lake City. Contact R. G. Moffat, 2656 Heather St., Vancouver 9, B. C.

**June 25–29**—Am. Soc. for Engineering Education, annual meeting, Ames, Iowa. Contact W. Leighton Collins, Univ. Illinois, Urbana, Ill.

**July 9–13**—Conference on Radiation Chemistry (Gordon Research Conferences of the Am. Assn. for Advancement of Science), New Hampton School, New Hampton, N. H. Two other Gordon Research meetings, both at Kimball Union Academy, Meriden, N. H., are **June 25–29** on Nuclear Chemistry and **July 2–6** on Chemistry and Physics of Isotopes. Contact W. G. Parks, University of Rhode Island, Kingston, R. I.

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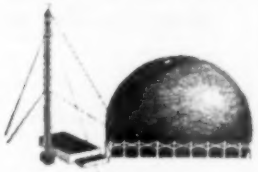

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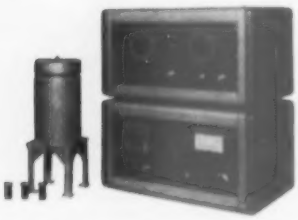
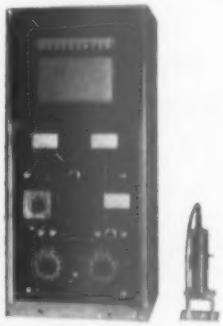


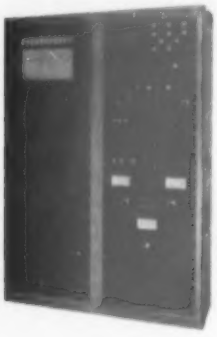
## Model 230 Manual Scintillation Spectrometer

Designed for qualitative analysis of radio-isotopes — singly, or in compounds and mixtures; for applications involving two or more isotopes and for low level counting work which requires background reduction. Addition of M-10 Mercury Shield almost completely eliminates background.



## Model 2300 Automatic Scintillation Spectrometer

Automatically sweeps between any two predetermined levels within range of 0 to 100 volts, then resets and repeats cycle. Includes Brown ElectroniK recorder for automatic print-out. Automatic sample changer (accessory Model S-24) changes sample when sweep circuit resets. Can also operate manually as single channel analyzer.



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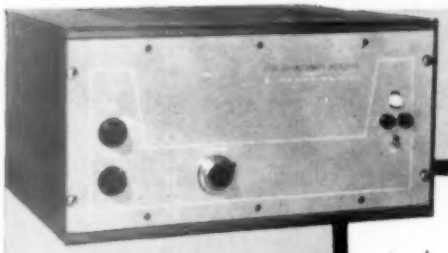

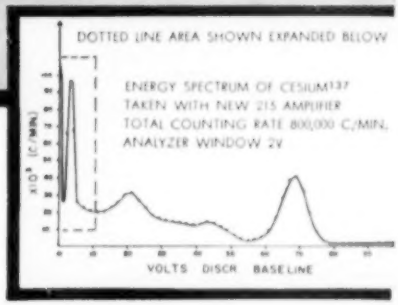
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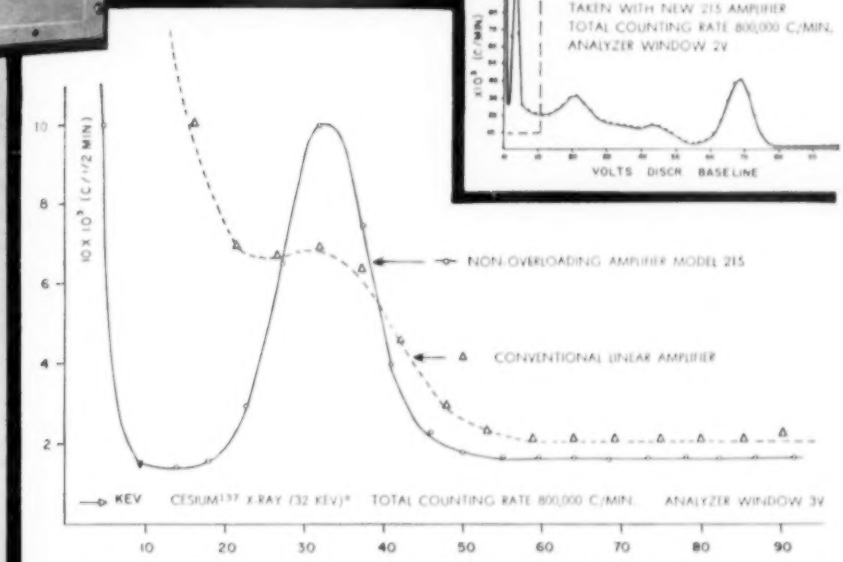
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CONVENTIONAL LINEAR AMPLIFIER
KEV CESIUM137 X-RAY (32 KEV)* TOTAL COUNTING RATE 800,000 C/MIN. ANALYZER WINDOW 3V

*Instruments used to obtain above curves were identical except for the amplifier, and included: Model 810 Scintillation Detector, Model 510 Differential Pulse Height Analyzer, Model 312 High Voltage Supply, and Model 131 Scaler.

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